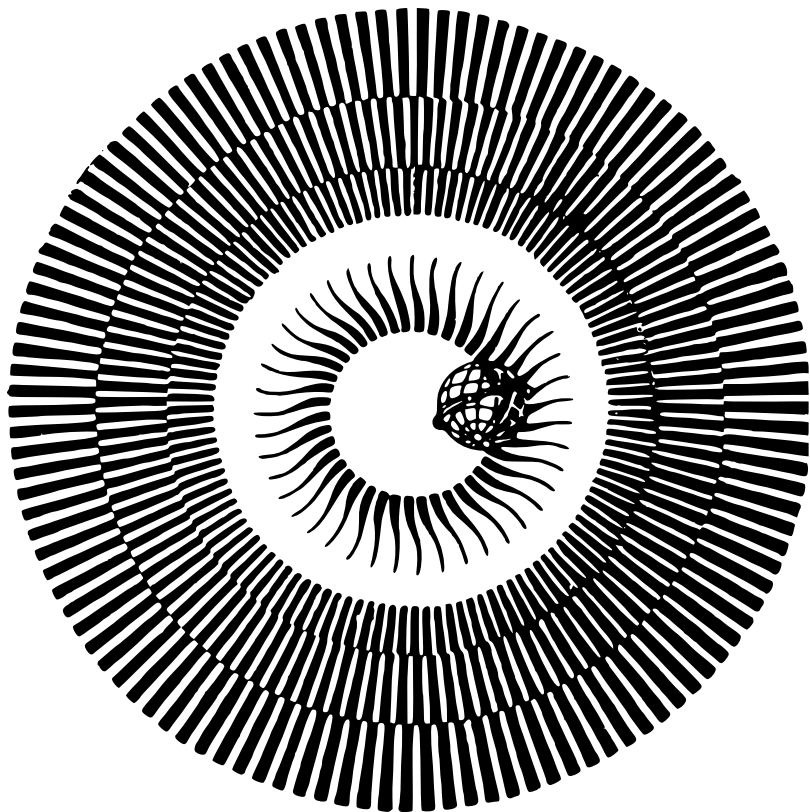
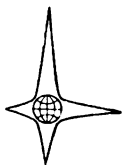


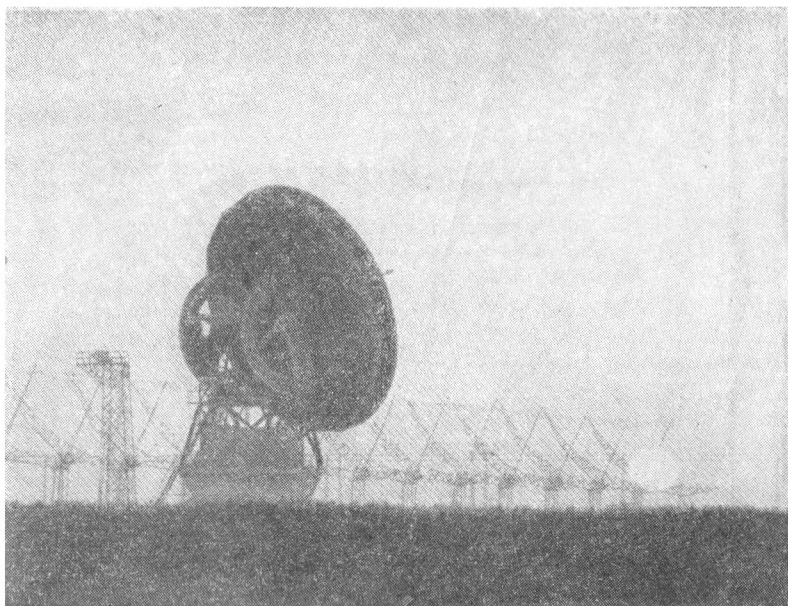
N. Pushkov B. Silkin



THE QUIET SUN



MIR PUBLISHERS



Н. В. ПУШКОВ, Б. И. СИЛКИН

**ВНИМАНИЕ!
СОЛНЦЕ
СПОКОЙНО**

ГИДРОМЕТЕОИЗДАТ

N. V. PUSHKOV, B. I. SILKIN

THE QUIET SUN

Translated from the Russian

by

George Yankovsky

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How can events 150 million
kilometres away affect us here on earth?
But if you have ever complained
of poor radio reception, if the compass
needle has ever gone
wrong, if you have ever wondered
what has happened to the
weather, the trouble most likely
has to be sought at this great distance.
Blame it all on the sun.
This book is an account
of that great world-wide undertaking—
the International Quiet Sun Year—
in which scientists
of over 60 countries participated.
Following the International
Geophysical Year, it disclosed
many secrets about our luminary.
Everyone who wants
to learn more about our sun
and how it affects the planet we live on
should read this book.

На английском языке

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From sun-worship to knowledge

"The Quiet Sun Year". Isn't there something oriental in the ring of this title? Like the "Year of the Dragon" in the calendar of the ancients, or perhaps the "Land of the Rising Sun"? Yet the International Quiet Sun Year, or IQSY for short, is not a poetic phrase but a rigorous term. It stands for one of the greatest scientific undertakings.

Let us take a fresh look at what seems to be quite an ordinary event. Every morning, as the dark of night fades away, a huge ball of fire bursts forth from the horizon lighting up the world about. A new day is born. This happens every 24 hours but still remains a miracle of nature. Men have always felt it to be of the utmost significance; in remote ages man worshipped the forces of nature, and the most magnificent of them all—the Sun.

Surely every people has passed through the stage of sun-worship. The primitive mind endowed with preternatural powers the regular succession of day and night, the seasons and other celestial and terrestrial events associated with the sun. The principal deity of the ancient Egyptians was Ra, the life-giving god. Melkarth (Moloch) was the deity worshipped by the Phoenicians and Carthaginians. To him human sacrifices were

made. The more humane Greeks and Romans of antiquity personified the sun as Phoebus, Helios, Apollo—the god of sunlight, music and poetry, the patron of the muses. The mighty Assyrian and Babylonian god Shamash, the ancient Persian Mithras, and the cruel deity Kezalkoatl of the Mayas depicted as a winged serpent are all personifications of the sun, great in its wrath and in its mercy. The ancient Slavs would greet the spring sun, the joyous stormy god Yarila, with dancing and merrymaking. After a long winter Yarila would arrive on a white horse and in white raiment with a handful of wheat spikes and would bury the strawman embodying winter. Thus in all corners of the world have people carved the image of the sun, honoured it with merrymaking and singing of songs, and have built temples and worshipped it.

Legends and myths were the first attempts to account for the unexplainable. Centuries passed before they gave way to knowledge based on facts. And, as always, the gain was not made without strife and sacrifice.

Some time about the year 434 B.C., the ancient Greek thinker Anaxagoras first conjectured that the sun was not the god Apollo but a burning mass of rock. Anaxagoras even tried to work out its size. He figured our luminary to be of the dimensions of his home peninsula Peloponnesus, which is about a hundred kilometres across. He had no proofs of course, it was simply guesswork. The teaching of Anaxagoras was in conflict with the religious dogmas of the time. The philosopher was arrested, accused of sacrilege and his very life was at stake.

The followers of the great Pythagoras who lived in the fifth to fourth centuries B.C. (most famous among them was Philolaus) were much in advance of their times. They proposed a model of the world in which the earth rotated on its axis and revolved about some central body. True, at the centre they placed not the sun but rather a kind of mystical central fire, around which moved the earth, the sun, the stars and the planets.

Engels described Aristotle as the "most universal head" among the ancient Greek philosophers. Still and all, his enormous authority that held sway for over a thousand years did a very poor service to astronomers. Aristotle espoused the geocentric system according to which the earth was the fixed centre of the universe, while the stars, the sun and the planets were in revolution about it in concentric circles. What is more, Aristotle maintained that unlike the earth substratum, the celestial substratum, or the ether, was immutable, non-transient and immortal, and that all celestial bodies were perfect and devoid of any flaws. Scholars of the Middle Ages adhered to this theory.

With the spring of the Renaissance came a flowering of the arts and the trades, people set out on long voyages, a real interest in the surrounding world burgeoned. January 7, 1610, was an historic day: Galileo Galilei trained his telescope on the sky for the first time. The moon, planets and stars might be said to have been discovered anew.

The surface of the moon was found to be not smooth as philosophers had been wont to say, but

rough with depressions and elevations in profusion, the Milky Way was found to consist of an enormous number of stars invisible to the naked eye, and around Jupiter he saw four satellites in orbit. This was a forevision, as it were, of the "heretical" system of Copernicus, according to which the earth and other planets revolve about a central luminary, the sun. Galileo's discoveries, which he published in *The Sidereal Messenger*, were like a thunderbolt from the blue.

In the summer of that same year Galileo turned his telescope to the sun and found dark spots on its bright disk. This was nothing new, however, for they had been detected in naked-eye observations much earlier. The ancient Chinese chronicles of the II-IV centuries mention "flocks of birds" appearing on the disk of the sun. In Nikon's Chronicle (Russia) for the year 1371 we read: "In that same summer there was a sign in the sun, spots that were black on the sun like nails. . ."

Galileo needed only a few weeks of observation to disprove the commonly held view that the spots were the shadow cast by the planet Mercury as it passed across the disk of the sun. The great Italian scientist carefully observed the spots for two years and came to the conclusion that the "spots are actual features on the surface of the sun, where they constantly appear and disappear, some in short intervals of time, others in longer intervals of time". He noticed a constant movement of each of the spots from left to right (from the eastern to the western limb of the solar disk). Certain spots disappear from sight and then come into view again at the other limb after

27 days. This is an indication that the sun is in rotation and the period of 27 days is exactly the time of one complete rotation of the sun on its axis.

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These and his other utterances in support of the great Polish astronomer brought down upon Galileo the full wrath of the inquisition.

We cannot here go into the whole story of the "discovery" of the sun that was begun by Galileo and continues to this day. Let us discuss our sun on the basis of modern scientific views.

Our own star

The distances that separate us from the stars are truly astronomical. Light racing at 300,000 km/s takes many years to cover them. The stars are so far away that the largest appear as points even in the most powerful telescopes.

But there is a star—our sun—unique among all others in that it is only 150,000,000 km away. Light takes eight and a third minutes to traverse this distance. The next closest star is Proxima Centauri, a whole $4\frac{1}{4}$ light years distant.

The sun sends to the earth 10,000,000 times more light than does Sirius, the brightest luminary in the northern skies. This is due solely to the small distance and has nothing to do with brightness or dimensions, for the sun is a very ordinary star, even somewhat smaller than usual; astronomers place it in the category of "yellow dwarfs." Still and all, one should not forget its cosmic dimensions: the diameter of this dwarf is 1,390,000 km, or 109 times that of the earth. The solar mass is 330,000 times that of the terrestrial mass, and its volume exceeds that of the earth by a factor of 1,300,000.

What is the sun made of? From what we

learned at school and from general everyday experience we know that all things about us are in one of three states: liquid, solid or gaseous. Now our sun is in a fourth state of matter: plasma.

It is hard to picture the physical processes developing in the solar interior. On the surface the temperature rises to $6,000^{\circ}\text{C}$, while the interior and the outer shell (corona) of the sun are believed to have temperatures in the vicinity of 15 or so million degrees. Pressures in the interior exceed those of air at sea level by a factor of a thousand million. Under these conditions, hydrogen and helium, which are the main constituents of solar matter, and all the other elements found on the sun (oxygen, nitrogen, magnesium, silicon, sodium, aluminium, carbon, iron, gold, etc.) pass into the little studied plasma state in which all the atoms are ionized (they lose the greater part of their electrons and acquire a considerable electric charge). This substance consists of atomic nuclei and free electrons in a state of extreme agitation. Raging nuclear reactions release energy equivalent to the simultaneous explosion of millions of hydrogen bombs.

Everything that takes place on the sun is directly related to life here on earth. You have probably noticed that at certain times a nearby radio station that you have been hearing perfectly every evening suddenly fades out completely. Then again, a broadcasting station or even a low-power amateur station from way off comes in clear as a bell.

There are times in the high latitudes of the Arctic and Antarctic when we have a total "radio blackout"—nothing comes through. Or the

compass needle suddenly deviates from the proper direction for no reason whatsoever. Now this is particularly important in polar regions where radio communication and correct directions are a matter of life and death for pilots, sailors, tractor trains in icy wastes and for anyone trekking the tundra with knapsack and compass.

What is the trouble? Who upset the radio communications? What made the compass needle falter in its duty? The guilty party lies 150 million kilometres from the site of the crime. The sun, it turns out, is responsible for this great diversity of phenomena that occur all about us.

A discovery with a strange history

Heinrich Schwabe, a provincial apothecary from the German town of Dessau, began his observations of the sun at the beginning of last century without in the least suspecting that this body could affect physical processes occurring on the earth.

Schwabe was a devotee of astronomy and dreamed of discovering an unknown planet in our solar system. But the telescope he had was rather weak and he did not hope to detect anything new on the background of the night sky. As Schwabe reasoned: "The situation is quite different in the daytime; it is much easier to notice the passage of a dark body across the bright disk of the sun."

But how was one to distinguish a planet from sunspots known since the time of Galileo or even earlier? Very simply: a planet should come into

view and disappear with regularity, in equal intervals of time. The only thing needed was patience, and that was one thing that Schwabe certainly had. The inhabitants of the old German town were wont to say: "The sun never rose above the cloudless horizon of Dessau without meeting Schwabe and his telescope." For over thirty years, every single day, Schwabe directed his telescope towards the sun and sketched the outlines of spots that he saw on the solar disk.

After twelve years of observations, Schwabe published his findings about the number of sunspots in a German astronomical journal. He also found that sunspots actively appear and disappear with a period of about 10 years. However, Schwabe did not publish his findings until 1843, after another five years of observations. For several years this discovery remained practically unnoticed until the great German scientist Alexander Humboldt described Schwabe's conclusions in his famous multi-volume work *The Cosmos* published in 1851.

Six years later, Heinrich Schwabe was awarded the Gold Medal of the Royal Society of London. Describing his merits, the President of this most important scientific body of those times said that his energy made possible the discovery of a phenomenon which astronomers had failed to notice during 200 years of observation.

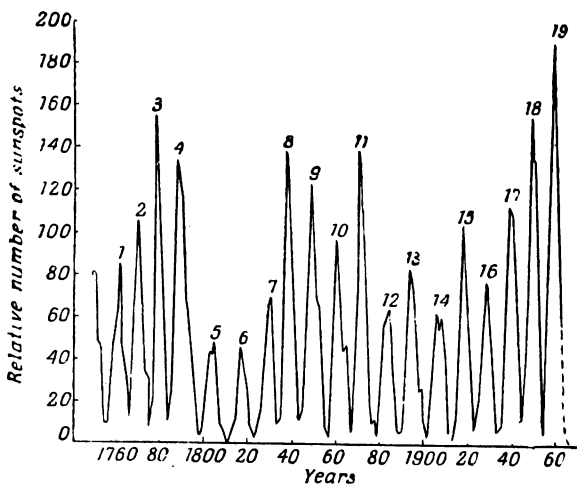
Today we know that the sun behaves in different ways. For a year or two it is relatively quiet and there are only a few spots on its "face". Then, like freckles in spring, they come out in ever increasing numbers from year to year. This build-up continues for about three to four years

until a maximum is reached. From then on the number of sunspots gradually diminishes.

The mean time interval between two sunspot peaks is about 11 years. But appreciable deviations have also been noticed. For example, after the maximum of 1788, 16 years elapsed before the next period when the sun again became stormy. In the 1820s and 1830s this interval came out to only 7.5 years.

That is how the 11-year cycle of solar activity was discovered.

Rudolf Wolf, a Swiss astronomer of the middle of last century, was first to generalize all previous observations and come to the conclusion



Mean annual variation of relative sunspot number. Peak labels indicate individual cycles

that the mean periodicity for the appearance of sunspots was 11.11 years. He also suggested an objective unit, or index, of solar activity based on the quantity of spots. This index became known as the "relative sunspot number" or Wolf's number. Since then the Zurich Observatory has been collecting observational data on sunspots from the whole world and for every day it derives the Wolf numbers that are used in all investigations of sun-earth relations.

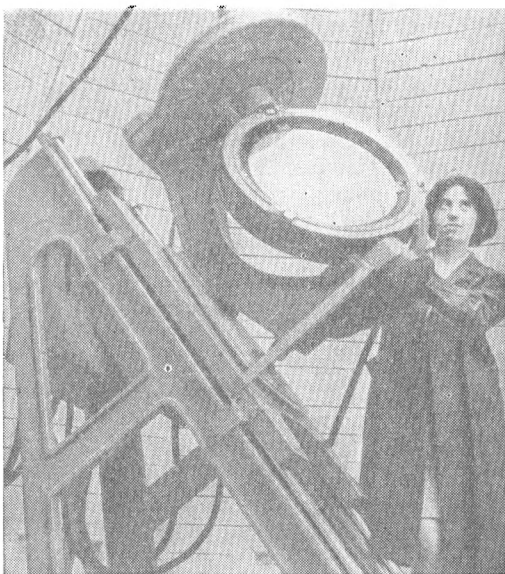
The number of sunspots varies from year to year. During the period of maximum there is hardly a day without observable sunspots, while during minimum nearly 80 per cent of the days of the year are without spots on the sun.

What is solar activity?

What we regard as the visible surface of the sun is the deepest observable layer of the sun's atmosphere, which is at a distance of 700,000 km from the centre of the sun. It is called the photosphere. We feel its breath every day. The name comes from the ancient Greek word meaning light. The "sphere of light" emits the greater part of the heat and light that we get from the sun.

The photosphere is the site of spots and of faculae, which are formations that are brighter than the photosphere itself. The rest of the photosphere is in the form of grains or granules on a dark background. Granules come in sizes from 400 to 1,000 km across.

It has long since been noticed that during solar eclipses, when the moon completely covers the disk of the sun, the limb is bordered by a thin reddish annulus. This ring is called the "coloured sphere", or chromosphere. In the 1890s new



Preparing coelostat mirror for observing solar
photosphere

instruments were invented for studying spectra and it became possible to observe the chromosphere not only during the few moments of a total eclipse.

The chromosphere is that part of the solar atmosphere which underlies the photosphere. It is about 14,000 km thick and consists of calcium, hydrogen and other gases.

The uppermost (outer) part of the sun's atmosphere is called the corona. This is a silverish

crown of the sun extending out to several solar radii. It was first observed only during eclipses, but in the 1930s the French astronomer Bernard Lyot devised an ingenious instrument called the coronagraph which makes it possible to eclipse the sun at any time and to view the corona on any clear cloudless day. That was a great achievement considering that during the three quarters of a century after the discovery of the corona in 1851 it had been observed for a total of less than one hour.

Since the time of Galileo, sunspots have been under the constant vigil of astronomers. It was found that most of them are short-lived and disappear within a few hours or days after coming into being. Only a few live for several months, but all the time their outlines are constantly changing. Sunspots appear dark because their temperature ($4,500^{\circ}$ to $5,000^{\circ}\text{C}$) is $1,000^{\circ}$ to $1,500^{\circ}$ lower than that of the surrounding areas.

No spots appear at the poles or on the equator of the sun. Their favourite place of origin is in the low latitudes between 25° and 5° in the southern and northern hemispheres.

Sunspots come in a variety of sizes from several thousands to tens of thousands of kilometres across. Features this size are readily visible to the naked eye. Occasionally a giant-size sunspot turns up. Such was the case in 1858, in February 1947 and in June 1959, when the area of a spot (rather a group of spots) came out to 180,000 million square kilometres. One hundred earth globes could have fitted into the 1947 group of sunspots. Incidentally, spots do not originate as giants. They are small when they appear, but in a

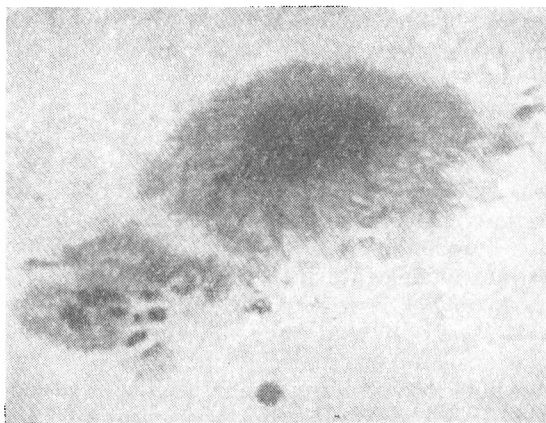
few days they rapidly grow to enormous proportions. Later they gradually shrink and disintegrate and then vanish completely. Sunspots usually appear in groups, not singly, each group consisting of tens of separate spots. Usually, however, a group consists of two large sunspots surrounded by a few smaller ones.

We recall Galileo's assertion that the spots appear to be moving over the disk of the sun from east to west due to the solar rotation. Sunspots closer to the western limb of the sun are called preceding spots, those closer to the eastern limb are known as following spots. As a rule, the following spots are of irregular shape and not so long-lived as the preceding spots. Upon reaching maturity, they rapidly disintegrate into smaller formations.

At the beginning of this century, the American astronomer George Hale established that sunspots have magnetic fields. Two spots forming a group have opposite magnetic polarity. This kind of group of sunspots is like the emerging tips of a horseshoe magnet hidden deep inside the sun. In the northern and southern hemispheres of the sun, the sign of the polarity of the preceding sunspots is always opposite. The polarity is north if it corresponds to that of the north magnetic field of the earth.

When after a few years of "rest" the sun enters a new cycle of activity, spots begin to form in latitudes about 30° to 35° .

As the years go by, the number of sunspots increases and they appear more frequently closer to the equator. During periods of peak excitation—maximum of activity—the sunspots become



Sunspots

frequent visitors near 15° to 20° and by the end of the cycle, they are still closer to the forbidden equator.

There is no real dividing line between two neighbouring cycles: for a year or two, the old and new cycles rather overlap, and spots of the outgoing cycle occur along with those taking over, but each one knows its place. The old-timers bunch up closer to the equator, while the new ones congregate in the higher latitudes.

Spots do not represent the only activity of the sun. It is simply that they are the most obvious formations and were discovered first.

Sunspots have permanent satellites, so-called faculae, which are the brightest regions of the photosphere. These bright moving filaments originate just a little before the accompanying spot and persist after the spot is gone. Long-living faculae sometimes last for about a year, while a spot rarely lives for more than four to five 27-day rotations of the sun. And the area occupied by a facula is on the average about four times that of a spot.

In general, faculae may be considered the creations both of the photosphere and the chromosphere. At times and quite unexpectedly, a portion of a facula is lighted up very brightly and we have what is called a solar flare (chromospheric flare). In 10 to 15 minutes it reaches peak brightness and then gradually decays. Some scientists believe that these flares are caused by nuclear decay, something in the nature of an explosion of a hydrogen bomb. Flare intensity is measured in area as Class 1 to Class 3+. You can imagine the scale of this phenomenon if the explosion of a

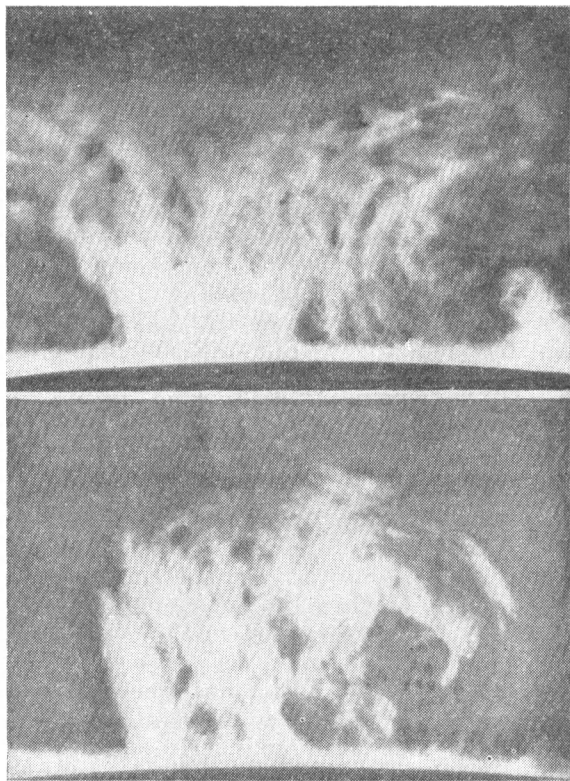
Class 3 flare occupies over three thousand million square kilometres!

Other manifestations of solar activity—prominences—belong both to the chromosphere and the corona. These are perhaps the most magnificent events on the sun. Prominences are gigantic splashes of flame, blazing clouds of a kind of eruptive origin. They project out of the sun's surface moving at speeds of many hundreds of kilometres a second. These fiery tongues can extend out into space for hundreds of thousands of kilometres. At times, if the speed exceeds 620 km/s, they can completely tear away from the sun and go off into interplanetary space.

Prominences consist of rarefied clouds with temperatures of several tens of thousands of degrees Celsius. They take on the weirdest forms on the background of the limb of the solar disk and call to mind spouting jets of water, arcs, trees and clouds.

There are not only rising prominences, but also descending ones when the solar matter moves downwards from the corona to the photosphere. This most often occurs over sunspots. Prominences have a variety of lifetimes. The most quiescent prominences persist for several solar rotations, while eruptive prominences disappear in just a short time.

The cycle of solar activity is accompanied by changes not only in the photosphere and the chromosphere, but in the corona of the sun as well. During maximum solar activity, we can observe multitudes of long coronal lines (rays) that are more or less uniformly distributed over the solar disk. During years of minimum activity,



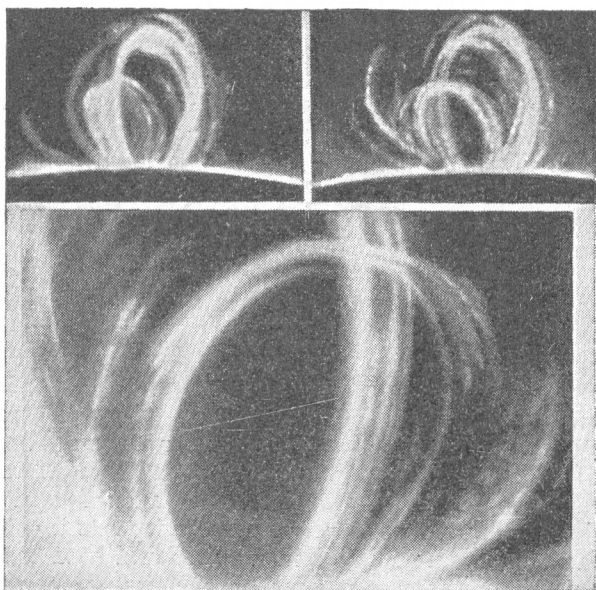
Solar flares

they shrink closer to the sun's equator. The corona is denser during maximum than during the period of minimum.

The various manifestations of solar activity observed in different regions of the sun are always interrelated in some way. It may be that the primal cause of these changes lies in the changes in the magnetic fields of the photosphere and chromosphere of the sun.

This is how events very often develop. A day or two after a local magnetic field appears in some region of the sun, faculae are seen to come to life in the vicinity; these are followed by the first signs of the sun's malaise—spots. The area of the faculae and spots increases. One or two weeks later, one can expect solar flares. Their lifetime is ordinarily drawing to a close as the sun completes one rotation on its axis. But in a short while a second phase of activity sets in: the faculae become smaller in number and then long quiescent filaments appear on the surface of the sun. These are prominences that project on the solar surface. Another few rotations of the sun and the visually observable events come to an end. But sensitive instruments show that in this place a special kind of magnetic field with a single pole persists for quite some time.

As early as last century it was noticed that magnetic storms have a strong tendency to recur roughly every 27 days. But this is precisely the time that it takes the sun to rotate once on its axis. There was one case when magnetic storms recurred every 27 days during 17 solar rotations. Quite obviously, having perceived this property, scientists are able to predict magnetic disturb-



Gigantic loop-like prominence on the sun (Sacramento Peak Observatory)

ances and certain other phenomena on the earth that are related to them.

The German magnetologist Julius Bartels, knowing that magnetic storms can appear and recur in the absence of any kind of apparent manifestations of solar activity, suggested as early as 1932 that recurrent magnetic storms are possibly due to the fact that the sun has special magneto-effective regions that report to us on their whereabouts by generating magnetic storms.

During the minimum of solar activity of 1953-1954, scientists correlated these recurrent storms with the appearance of single-pole magnetic fields during the relatively short time from April 1953 to January 1954 and found a rather definite relationship between them. However this interval of observations is too small for an exacting specialist to draw any definitive conclusions. At the present time, all hopes are being pinned on studies of the results of the International Quiet Sun Year.

Almost 200 years ago scientists first turned to the sun in attempts to explain the origin of magnetic storms and the polar lights (auroras). Even at that time they maintained, though they lacked proof, that the sun might be sending to the earth some kind of minute charged particles, corpuscles, that generate magnetic disturbances and the auroras.

To verify this supposition, at the end of last century the Norwegian physicist Kristian Birkeland carried out his famous experiments in irradiating a magnetic model of the earth (terrella) with cathode rays (electrons). The terrella was a spherical electromagnet placed inside a large cathode-ray tube; the sun was the cathode that emitted streams of electrons. It was found that the electrons are deviated to the polar regions of the terrella and impinge on its night side.

Birkeland's experiments were later corroborated by rigorous mathematical calculations of the motion of charged particles in the magnetic field of the terrella. The Norwegian mathematician Carl Störmer, who made the computations, later became a devoted investigator of polar auroras.

Thence came the Birkeland-Störmer theory of magnetic storms and the aurora.

This theory states that at definite instants, comparatively narrow but dense fluxes of charged particles of the same sign may be ejected from certain active regions of the sun. But due to mutual electrostatic repulsion a dense flux of particles of one sign cannot persist during the time of flight of the particles from the sun to the earth. The Birkeland-Störmer theory could not account for this fact.

A new hypothesis was advanced in the 1920s which stated that solar fluxes consisted of an equal number of positively and negatively charged particles and that, hence, the stream or flux was, on the whole, neutral. Another two decades later it was suggested that the sun constantly emits streams of particles of both signs. These streams occasionally build up and generate magnetic storms. The idea was put forth that there is a constant solar wind, or corpuscular radiation of the sun. This is the way it developed.

Since remote antiquity people have been amazed, and more often frightened, by the appearance of comets. Astronomers have long noticed that the tails of these visitors from deep space always point away from the sun, no matter what their direction of motion is.

This was first explained by the effects of light pressure which was discovered by the Russian physicist P. N. Lebedev. However, about 20 years ago the German scientist L. Bierman proved that it was impossible to account for such behaviour of a cometary tail by light pressure alone. He conjectured that the gases forming this tail are

whipped about by streams of solar particles and he computed the speed of this wind to be about 500 km/s.

The hypothesis of solar wind does not run counter to anything we know about the sun and circumterrestrial space. But it remained a hypothesis until interplanetary probes proved just recently that between our planet and the sun there is a stream of corpuscular radiation emitted by the sun and travelling with velocities from 300 to 600 km/s.

The period of the IQSY was particularly convenient for a comprehensive study of the sun and the effects it exerts on our planet because comparatively few large-scale events occurred on the sun during this period, and those that did were isolated and could be traced throughout their lifetimes, from birth to total decay.

During the IQSY, the sun was taken under particularly careful surveillance. Over a hundred observatories participated: 19 in the U.S.S.R, 17 in the U.S.A., 7 in France, 5 in Japan, and 4 each in the German Democratic Republic, India, the German Federal Republic, Canada, Italy, etc.

To keep the sun under round-the-clock surveillance, and not let a single event on the sun escape notice, the different observatories distributed their observational times so that the sun was always under observation. This made it possible to study variations of solar activity in time and to correlate them with geophysical phenomena observed by ground stations and recorded in interplanetary space by satellites and space probes.

These observations made it possible to predict solar activity and choose the best and safest times for space flights. Finally, they suggested to geophysicists times for more frequent observations during events of interest that might be expected.

The central event in solar studies during the IQSY was the joint investigation of active regions of the sun which was conducted on the initiative of Soviet geophysicists between April 1 and September 30, 1965. Many first-class solar observatories in different countries participated in this work. The aim was to obtain diverse detailed information about the origin, development and decay of active regions on the sun.

Apart from these special and co-ordinated (in time) observations, many observatories carried out their own individual studies in accord with the IQSY. Some made careful measurements of the magnetic fields of the sun in order to compile an exact magnetic map of the sun for every day of the IQSY. Others engaged in high-speed cinematography of the chromosphere to obtain a film of the sun for the two-year period. Still other observatories sent instruments aloft in balloons, rockets, and satellites to photograph the solar corona outside the atmospheric mantle of the earth. Some observatories bounced radar signals off the sun's surface. Others concentrated on the effects of the solar wind on cometary tails. Finally, some investigators collected all their instruments and devices and travelled thousands of kilometres to a small atoll in the Pacific Ocean (Manuae in the Cook Islands) where a total eclipse of the sun was observed for five minutes on May 30, 1965.

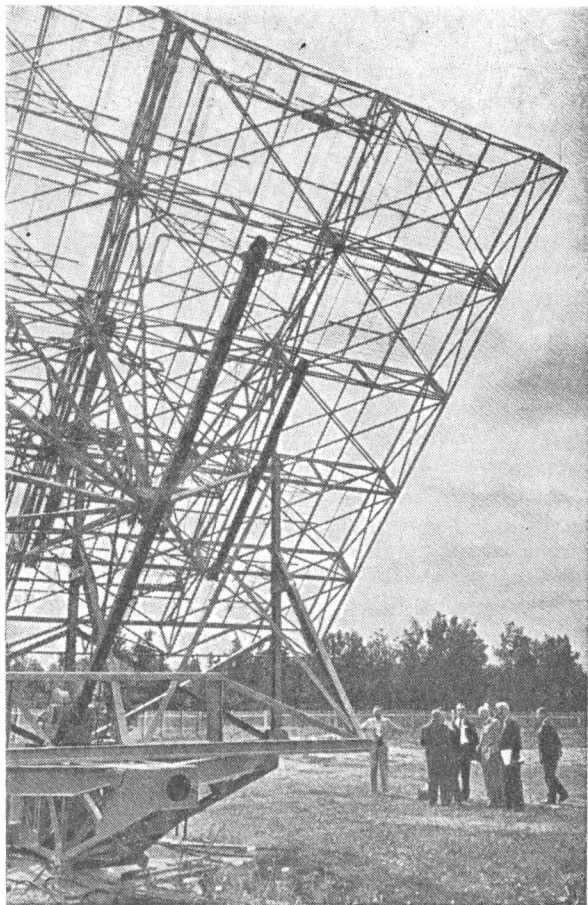
Everyone has felt the ultraviolet sun-tan rays, the infrared heat rays and has seen the visible light rays that the sun sends to the earth. But, like other stars, our sun does not confine its activities to this radiation alone.

The visible light is in the form of electromagnetic oscillations of wavelength about 0.00003 to 0.00006 cm. But scientists have long supposed that the sun should be emitting much smaller and much longer wavelengths. The point is that the earth's atmosphere opens up only a narrow window to the optically observable visitors from the sun and we receive but a small portion of the solar radiation. The rest—radiation of wavelength shorter than 0.29 micrometre or longer than 3 micrometres—is absorbed by the atmospheric ozone or water vapour.

It was during World War Two, at the height of the air battle over England. Every day German aircraft tried to break through to London, and the whole British anti-aircraft service was on guard. On February 28, 1942, radar screens suddenly exhibited unusually strong radio interference. What could this be? A new trick of the enemy to blind out the radar installations? No, because no enemy planes appeared.

What actually happened was that radio emission of the sun had interfered in radar affairs. On that day the sun's disk exhibited a large spot, and there was a solar flare that lasted about three hours. This solar event "echoed" 150,000,000 km away on the earth in the form of radio interference.

That was the beginning of a new science—radio astronomy. Today nearly every astronomi-



An IZMIRAN installation for studying radio emission of
the sun

cal observatory, in addition to the customary optical telescope, has spherical, parabolic, criss-cross and other types of radio antenna that are tuned in to the radio waves coming from outer space.

With the aid of a great variety of apparatus—radio telescopes, radio polarimeters, radio spectrometers, interferometers—we can record streams of waves of different frequency, determine the polarization, watch changes in the spectrum, find the spot of the solar disk that is ejecting this radio flux, and draw up charts of radio brightness of the sun on different wavelengths.

Today we have instruments capable of receiving radiograms from the sun in the range from a few millimetres to 30 metres. The window into space through which we now study the stellar world has widened by 17 to 18 times and we can keep up observations in any weather, even when the eye and optics are powerless.

The radio emission of the sun has turned out to be a very sensitive indicator of the level of solar activity: depending on the degree of solar activity, it can increase or decrease hundreds and thousands of times—many times more than visible radiation, which is rather constant and but feebly depends on the moods of the sun. Solar flares are attended by extremely intense variations of intensity of radio emission in the form of outbursts of varying duration. In some cases, the disturbance first begins on the shorter wavelengths and then sooner or later moves into the longer wavelengths.

The radio emission of the quiescent sun, which at the time has no active formations, is of ther-

mal origin, like the electromagnetic oscillations in the optical range. Therefore, it too varies with the cycle of solar activity, only the limits are small.

When active features appear on the sun, the additional radiation of the disturbed sun is of a non-thermal nature. It is superimposed on the radiation of the quiescent sun. The nature of the perturbed radiation of the sun is still obscure. It may be that it is excited by streams of electrons ejected from the inner regions of the sun as they pass through the solar corona.

The atmosphere of the sun is strongly ionized, so that it absorbs radio waves, particularly the longer wavelengths. Waves in the metre range are emitted by the sun only if they are generated in the corona, where the temperature must be in the vicinity of a million degrees Celsius. The high temperatures of the corona make it the basic source of X-radiation of the sun. Of the radio waves generated in the photosphere and chromosphere, the corona transmits only those in the millimetre and centimetre ranges. By recording the radio emission of the sun in different wavelengths, one can judge the activity of the sun at different depths in the solar atmosphere.

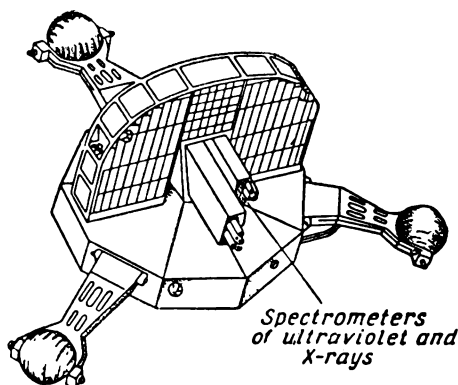
Scientists have correlated changes in area of sunspots with variations in the intensity of radio emission of the sun on various wavelengths. They have been found to agree very well with intensity variations of radiation of wavelength 10 cm. That is why intensity of radio emission on wavelengths of 10 to 20 cm is now used as an index of solar activity alongside the Wolf numbers mentioned earlier.

Some of the sun's messages do not reach the surface of the earth: ultraviolet and X-radiation are absorbed in the upper levels of our atmosphere, and, as will be seen later on, the corpuscular radiation is captured and retained by the earth's magnetic field at large distances. Light waves are greatly scattered in the atmosphere by air currents, clouds, and dust. Under such conditions it is particularly difficult to observe the corona whose brightness near the disk of the sun does not exceed one-millionth of that of the disk and rapidly falls off with increasing distance from the sun.

For this reason, astronomers strive to carry out solar observations outside the atmosphere or at least beyond its densest and most contaminated portion by placing instruments in aircraft, balloons, rockets and satellites. The first good photographs of the sun's corona were obtained on March 5, 1964, at a balloon-launching scientific station at Palestine (Texas, U.S.A.). When the balloon carrying a coronagraph reached an altitude of about 30 km the instrument automatically locked on the sun and the telemetric equipment began to relay information to the earth. Although the parachute system jammed and disaster was imminent, the film was finally brought down undamaged.

For the first time, these photographs recorded coronal streamers outside of eclipse at distances from 1.8 to 5.25 solar radii from the centre of the sun's disk. One hundred and eighteen photographs were made in 5.5 hours, a whole album dealing with the life of the sun.

Though it will take quite some time to process



Orbiting Solar Observatory (OSO) satellite (United States)

all the materials, certain preliminary conclusions may be drawn from this experiment. An interesting thing is that the corona was in a state very typical of the minimum sunspot period. Preparations are now in progress for launching similar instruments in artificial earth satellites.

For more than ten years now researchers have been measuring the intensity of the ultraviolet and X-radiation of the sun and photographing the sun in these rays. Rockets have repeatedly been launched during solar flares. It has been established that during flares the intensity of ultraviolet radiation does not increase so much as was formerly thought. But great changes take place in the flux of X-radiation during these periods.

Studies of the solar spectrum by rockets are of great interest for those who want to know how the sun affects the upper layers of the earth's at-

mosphere. The drawback to rocket measurements is their brief duration, and scientists want to have a continuous record of solar emissions beyond the atmosphere of the earth.

Satellites have come to their aid in this research. They carry stabilized platforms capable of maintaining an exact orientation on the sun. One of the first in this family was the American satellite OSO (Orbiting Solar Observatory) launched into orbit in March 1962. It carried instruments for measuring X-rays and ultraviolet radiation of the sun. In June 1963 the United States launched another satellite Solrad (for solar radiation), which for a month and a half measured the X-radiation of the sun.

The beginning of 1964, the start of the IQSY, was a real harvest time with two satellites launched: the Soviet Electron 2 and the American Solrad 2. These vehicles obtained very valuable information about solar X-radiation. It was found that when passing from maximum solar activity to minimum, there is a great attenuation in X-rays from the sun: a 10-fold decrease on the 50-angstrom wavelength, and a 50-fold decrease on 10 angstroms.

The telemetry of the Solrad satellite transmitted information continuously and not only when the satellite passed over U.S. territory. This made possible reception in many countries. One of the transmissions (in September 1964) was received by the astronomical observatory Arcetri in Florence, where the great Galileo observed sunspots with his telescope. The reception was good and permitted predicting the immediate development of events on the sun. The observations be-

gun by Solrad were continued by the OSO 2 satellite launched in February 1965.

Thus the IQSY initiated continual solar observations by satellites, which undoubtedly will be continued in the future. The time is probably not far off when we will be able to obtain television images of the sun in X-rays and ultraviolet light by means of satellites.

The science-fiction writer Ray Bradbury relates of a trip to the sun during which his astronauts attempt to pick up for research a bit of stellar material with a gigantic spoon. This is pure fantasy of course, but investigators are already able to "touch" the sun, if radar probing can be called touching.

Radio waves of length 8 to 12 metres are being used to probe the sun; they are reflected from the corona at about 350,000 km from the surface and return to the earth to tell us about the structure and properties of the sun.

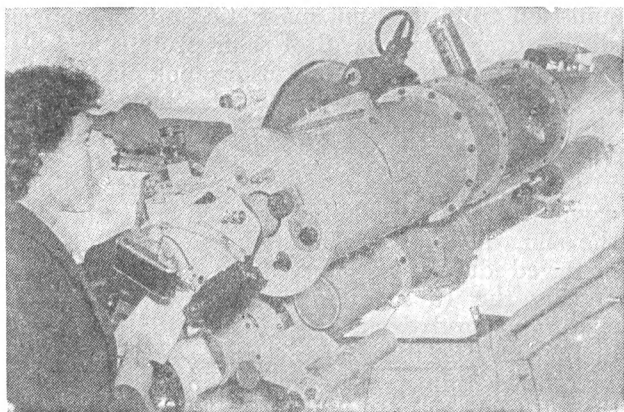
Since the start of the IQSY, these measurements have been conducted daily. Studies of solar plasma ejected in solar flares were repeatedly made when the Soviet and American probes headed for Mars and Venus encountered streams of emission from the sun. United States IMP (Interplanetary Monitoring Platforms) satellites and their Soviet counterparts of the Electron series moving in eccentric orbits that extend beyond the earth's magnetic field have the same purposes.

Now, when the IQSY has completed its activities, and astronomers, astrophysicists and geophysicists are studying the results, one thing is certain. The work done over the past 300 years

since 1649 in accumulating information about the sun (this, incidentally, was the twentieth 11-year solar cycle) has born fruit. We have learned much during this time.

During 1964 and 1965, as was predicted, we had a period of minimum solar activity. Although the first sunspot in the current cycle appeared in August 1963, the second was born only at the very end of February 1964. And the old spots left over from the preceding 11-year cycle gradually vanished, the last one fading out in May 1965.

The mean annual relative number of sunspots diminished from 34 in 1963 to 10 in 1964 and rose to 15 in 1965. Using three indexes (number of sunspots, radio emission on 10 cm, and intensity of flocculi) we find the minimum of solar activity in July 1964. During this period, the



Soviet solar-flare telescope (AΦP-2)

mean relative number of sunspots per month was only three. Then the activity began a slow and irregular build-up.

A characteristic feature of the minimum between the 19th and 20th cycles was that there were comparatively short periods when the sun had no spots at all; the relative sunspot number was then zero. This occurred on June 26-28, July 26-30, September 16-27, 1964 and April 4-5, 1965.

The World Forecasting Centre sent out over 300 alerts during the IQSY calling on geophysicists to expand observations and take particular care in view of the interesting events in sun-earth relations. The first alert signalled an approaching magnetic storm, and the possibility of auroras was announced on January 3, 1964 after the IQSY had barely got under way.

The solar flares attended by enhanced radio emission from the sun, magnetic and ionospheric disturbances, the arrival of solar protons and disruptions of radio communications took place mainly in the region of old-cycle spots. Such also were the flares of February 5, 1965 and April 16 and 17, 1965.

The new, twentieth, cycle was exceedingly asymmetric in distribution of active features on the sun, differing from anything that had been observed during the preceding hundred years. During the 16 months of the new cycle, sunspots appeared exclusively in the high latitudes of the sun's northern hemisphere.

Another thing worth mentioning is that although solar activity during the IQSY was somewhat higher than during the previous mini-

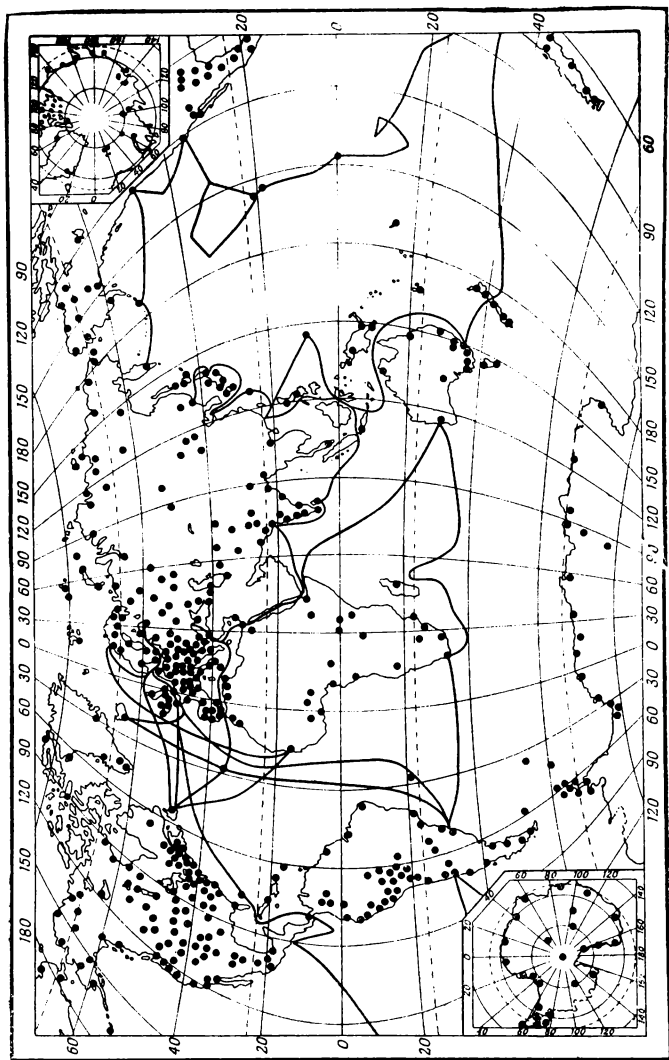
imum of 1954, the geomagnetic activity was less this time than during the previous minimum. Hence, the time for the International Quiet Sun Year was correctly chosen. The IQSY brought rich material for studying solar-terrestrial relations under a quiet and disturbed sun.

The chapters that follow are devoted to the effects that the quiet and stormy sun has on various physical processes occurring on our planet.

The project and its outline

The deeper scientists penetrated into the mountain of materials of the International Geophysical Year, the more obvious it became that valuable as these findings were, they did not provide answers to all the questions, particularly since the period of the IGY was unusual: maximum solar activity and an utterly unheard of intensity. Of course, the disturbed behaviour of our sun during this period yielded a picture of the sun in a state of extreme unrest. But to obtain some idea of the variations of solar-terrestrial relations during the cycle of solar activity, one had to collect a broad range of information about the sun during the quiet period, and then correlate all the available facts.

There were other arguments as well. Joint solar and geophysical investigations during the period of minimum solar activity had never before been conducted. Although the Second International Polar Year (1932-1933) had covered a similar minimum period, the geophysical observations at that time did not embrace the entire globe: the



Antarctic was missed and few observations were made in the equatorial latitudes. Besides, geophysicists did not have instruments for continual observation of the auroras and cosmic rays and there were no rockets and satellites at that time.

The first step was taken in August 1960 when the International Geophysical Committee, made up of representatives of the various international scientific unions dealing with investigations of the sun and geophysical phenomena, set up a commission to work out the programmes of scientific research during the next minimum of solar activity. The project submitted by the commission was approved by the International Geophysical Committee in January 1961. It was decided to conduct a fresh general search for facts about solar-terrestrial relations and to call it the International Quiet Sun Year, IQSY. This decision was supported by the International Astronomical Union, the International Union of Geodesy and Geophysics, the Union of Pure and Applied Physics, the Scientific Radio Union, the Committee on Space Research, and the Committee on Antarctic Research. The World Meteorological Organization also joined in. The project was approved by the International Council of Scientific Unions and received the support of UNESCO which called upon the various countries to participate in the IQSY.



Some IQSY stations and observatories that studied geomagnetism, auroras, the ionosphere, solar activity and cosmic rays; also indicated are routes of expeditions of the non-magnetic ship *Zarya* during the IGY and IQSY

The participants of the IQSY research programme met at assemblies in Paris in 1962 and in Rome in 1963. Here they revised the programme of work, co-ordinated methods and aims, distributed roles among the scientists of the various countries and agreed upon the order of exchanging materials obtained.

The academies of sciences and similar institutions of about 70 countries responded to the call for co-operating in this march for facts about our planet. They included scientists from Argentina, Australia, Austria, Belgium, Bolivia, Brazil, Bulgaria, Burma, Canada, Ceylon, Chile, Colombia, Congo (Kinshasa), Cuba, Czechoslovakia, Democratic Republic of Vietnam, Denmark, East Africa (Kenya, Uganda), Eire (Ireland), Ethiopia, Federal Republic of Germany, Finland, France, German Democratic Republic, Ghana, Great Britain, Greece, Guatemala, Hungary, Iceland, India, Indonesia, Iran, Iraq, Italy, Izrael, Jamaica, Japan, Korean People's Democratic Republic, Laos, Mexico, Mongolia, Netherlands, New Zealand, Nigeria, Norway, Pakistan, Peru, Philippines, Poland, Portugal, Republic of South Africa, République Malgache, Rhodesia, Rumania, Senegal, Sierra Leone, South Korea, South Vietnam, Spain, Sweden, Switzerland, Turkey, United Arab Republic, U.S.A., U.S.S.R., Venezuela, Yugoslavia*.

In a word, all scientifically and technologically developed countries and many others that

* Actually, the number of countries participating in the IQSY was even greater because some of the new states of Africa lacking facilities of their own put their territories at the disposal of other countries for observational purposes.

have just recently taken that path of development raised the flag of sun-earth science.

The IQSY, it must be said, is not only an undertaking dedicated to the noble aims of deciphering the secrets of nature. It is also an effective means for strengthening friendship, and scientific and business relations between the nations.

Though the preparation for the International Quiet Sun Year was simplified by the extensive experience accumulated during the IGY, the job was not an easy one at all. An International Committee was set up to take charge of the IQSY.

This Committee consisted of representatives of scientific unions participating in the IQSY. The President was Professor W.J.G. Beynon (Great Britain), Vice-Presidents Dr. M. A. Pomerantz (U.S.A.), Dr. N. V. Pushkov (U.S.S.R.), and Professor G. Righini (Italy).

Reporters (also members of the Committee) were designated to manage and co-ordinate the investigations of each branch of science included in the programme of the IQSY. Dr. W. L. Godson (Canada) was reporter for meteorology, V. Laursen (Denmark) for geomagnetism who was later replaced by J. O. Cardus (Spain), J. Paton (U.K.) on auroras, Dr. D. Barbier (France) on air-glow, Prof. W. E. Dieminger (F.R.G.) on the ionosphere, Prof. M. A. Ellison (U.K.) and, after his death, Dr. R. Michard (France), on solar activity, Prof. S. N. Vernov (U.S.S.R.) on cosmic rays, Dr. M. Nicolet (Belgium) on aeronomy, Dr. Herbert Friedman (U.S.A.) on space research, and A. H. Shapley (U.S.A.) on "World Days" (these will be discussed later on). In addition,



representatives of the World Data Centres where all countries had to send in their observational materials also became members of the Committee: Dr. Hugh Odishaw (U.S.A.), Candidate of Geographical Sciences V. F. Burkhanov (U.S.S.R.), Prof. Takesi Nagata (Japan), and representatives of a number of international bodies interested in solar-terrestrial relations: the World Meteorological Organization, the Committee on Space Research, the Committee on Antarctic Explorations. Dr. S. M. Minnis (U.K.) was named Secretary of the Committee of the IQSY.

The new undertaking had to have an official



Headquarters of the International Quiet Sun Year at a meeting in Moscow, September, 1965.

Left to right: Secretary, S. M. Minnis (U.K.), Vice-President, Prof. N. V. Pushkov (U.S.S.R.), President, Prof. W.J.G. Beynon (U.K.), Vice-President, Prof. G. Righini (Italy), Prof. V. A. Troitskaya (U.S.S.R.), Corresponding Member, U.S.S.R. Academy of Sciences, S. N. Vernov, Dr. H. Odishaw (U.S.A.), Dr. D. Martin (U.K.), Dr. Z. Švestka (Czechoslovakia), Prof. B. L. Dzerdzeyevsky (U.S.S.R.)

emblem. From all parts of the world came suggestions, some were abstract cross-word puzzles in which it was hard to make out anything, others old-fashioned gravures with allegorical figures and long Latin inscriptions borrowed from forgotten manuscripts. The International Commit-



Emblem of the IQSY

tee decided upon a combination of the best elements of the American and Soviet designs.

That was how the emblem was born that now adorns geophysical instruments set up at both poles, in all climatic zones, and on all continents of the planet, and which is found on all publications relating to the IQSY. Here, superimposed on a symbolic sun with rays extending out into space is the familiar emblem of the International Geophysical Year. This stresses the continuity of the work done during IQSY and the IGY. Again, the symbolism of the IGY is largely in accord with the idea of the IQSY: here we have the orbit of an artificial satellite circling the planet, and the tilted globe displaying the polar region which is most important to geophysics.

Incidentally, the high latitudes were again in the focus of attention during the IQSY. Both polar caps, which only a decade or so ago were so lifeless, were subjected to a real scientific inva-

sion. The Soviet "North Pole" drifting stations, which are now on a permanent basis, one replacing the other, continue along IQSY lines to "clean up" this blank spot of the Arctic. Icy Antarctica again came out ahead of all continents as to proportion of people with higher education. Two new stations, Novolazarevskaya and Molodyezhnaya, were added to the old foreposts of Soviet Antarctic science: the observatory at Mirny and the Vostok station located near the geomagnetic pole and the cold pole.

The Americans converted McMurdo into their Antarctic scientific station, equipped the Amundsen-Scott station at the south geographic pole, and opened up a new scientific base at Eight.

Fresh parties of researchers arrived from France, Chile, England, Argentina, Australia, and Norway. Stations and observatories were specially outfitted for the IQSY with new apparatus for observations (during the period of low solar activity) of the magnetic field of the earth, the auroras, cosmic rays, the propagation of radio waves, the weather, and the climate.

Other researchers from countries that did not have their own stations here in Antarctica also participated in Antarctic studies. The Soviet stations accommodated specialists from Hungary, the German Democratic Republic, and Czechoslovakia. American geophysicists were allowed to conduct observations at the Vostok station and Soviet workers visited the American station at McMurdo, and their fruitful co-operation has enriched the storehouse of universal knowledge.

All countries taking part in the IQSY set up national committees of the IQSY with the partic-

ipation of prominent specialists. These committees were often confronted with formidable tasks. For example, the geomagnetic observatory Helwan in the United Arab Republic had to be transferred to another site because a nearby railway had recently been electrified and interference might have spoiled important observations.

In preparation for the IQSY, Japanese scientists organized a publicity campaign to obtain funds for the construction of a new ice-breaker, without which the Japanese scientific Antarctic station at Syowa would not have been able to function. British geophysicists increased their staff at the Halley Bay station to a record number of 98.

In the United States, powerful radio installations were put into operation for radar studies of the solar corona. Canada built a new radio telescope and radiometer for recording solar radiation and radio outbursts on the sun. With the aid of Soviet scientists, the Cuban Academy of Sciences set up magnetic and ionospheric stations. Australia manufactured cameras for determining the altitudes of auroras at the Antarctic station of Mawson. An international station for rocket probing of the atmosphere was set up in India on the magnetic equator. The Mongolian People's Republic established an observatory for observing the sun's corona. Ultra-sensitive apparatus (supermonitors) for continual registration of cosmic-ray intensity were set up at the Pic du Midi mountain observatory in France and at Port-aux-Françaises on the French island of Kerguelen.

In the Harz mountains (Federal Republic of Germany), an observatory was built for observ-

ing satellites launched according to the programme of the IQSY. In Switzerland, the high-altitude towns of Arosa and Davos, known mainly as resort sites and places for ice-skating competitions, welcomed meteorologists from all over the world who came here to compare their instruments.

Dozens of countries in all continents of the world were involved in this great undertaking. One country designed new equipment, the use of which enabled all participants of the IQSY to improve observations, while another country worked out unified procedures for investigations and processing of results.

The Soviet Union took an active part at all stages and occupied a leading place as regards the number of stations and observatories participating in the IQSY. The national importance of this major scientific venture is stressed by the fact that the Council of Ministers of the U.S.S.R. passed a special resolution on preparations and entrusted the work to the Interdepartmental Geophysical Committee of the Presidium of the U.S.S.R. Academy of Sciences, which had earlier organized and conducted the work of the IGY in the U.S.S.R. This Committee, headed by V. V. Belousov, Corresponding Member of the U.S.S.R. Academy of Sciences, was charged with co-ordinating the entire work of Soviet participants in the IQSY and representing their interests in international scientific bodies. This Committee set up a Working Commission of the IQSY made up of prominent Soviet specialists in the field of solar-terrestrial relations.

Work got under way immediately in all cor-

ners of the country. In Alma-Ata, Kiev, Leningrad, Murmansk new buildings for multi-purpose magneto-ionospheric stations went up. In Georgia, a subterranean cosmic-ray laboratory was built. In the far-off Eastern Sayany mountains, on Mt. Naran, which in the Buryat language means "sun" and where our luminary is visible no less than 300 days a year, we set up a high-altitude solar observatory of the Siberian Institute of Terrestrial Magnetism, the Ionosphere and Propagation of Radio Waves. Many stations connected with the IQSY installed new improved equipment.

Among the active participants of the IQSY were scientific institutions of the U.S.S.R. Academy of Sciences and a number of academies of the union republics of the country. The Shmidt Institute of Terrestrial Physics and the Institute of Atmospheric Physics in Moscow, the Polar Geophysical Institute in Murmansk, the Siberian Institute of Terrestrial Magnetism, the Ionosphere and Propagation of Radio Waves in Irkutsk, the Astrophysical Observatory in Riga, the Abastumani Astronomical Observatory in Georgia, the Institute of Geophysics in Dushanbe, the Institute of Space Physics Studies and Aeronomy in Yakutsk, the Pulkovo Observatory, the Crimean Astrophysical Observatory in Simeiz, the High-altitude Astronomical Station in Kislovodsk, and many other scientific institutions conducted observations according to the unified programme of the IQSY.

The country's oldest centres of science—the universities of Moscow, Leningrad, Kiev, Odessa, Kazan, Tbilisi, Tomsk, Kharkov, and Gorki—took an active part in the IQSY.

A big contribution to the IQSY was made by the scientific institutions of the Chief Management of the Hydrometeorological Service: the Chief Geophysical Observatory named after A. I. Voeikov, the Arctic and Antarctic Research Institute in Leningrad, the Central Aerological Observatory near Moscow, and others. The Chief Management of the Hydrometeorological Service equipped a total of 425 stations for observations of atmospheric phenomena.

As usual, the scientists of the Soviet Union worked in close co-operation with IQSY participants from the other socialist countries. Problems dealing with the IQSY were frequently discussed at meetings of the geophysicists of the socialist countries.

An extensive and diversified programme of scientific studies was carried out during the IQSY by the Institute of Terrestrial Magnetism, the Ionosphere and Propagation of Radio Waves of the U.S.S.R. Academy of Sciences located near Moscow. Which is quite natural, since the scientific team of this institute specializes in deciphering solar-terrestrial relations.

The institute set up a body with the rather exotic title "Eurasian Warning Centre" with two subcentres: one in Prague and the other in Irkutsk. What is this body?

In an attempt to catch every single interesting event in solar-terrestrial interrelations, a special international system called the "World Day Service" was established. World days were intervals of time during the IQSY for which there were reliable predictions of interesting geophysical events, for instance, a solar eclipse, an earth

encounter with an unusually large number of meteors, etc. During such days or even in the course of whole weeks at a time, the geophysicist would carry out intense measurements and observations with higher than usual frequency. But suppose interesting unexpected events developed on the sun that could not be predicted far into the future. The World Day Service would send out a warning and call for extra observations.

This is how it was done. In Tokyo, Moscow, Paris, and Washington were special forecasting centres that predicted magnetic and ionospheric disturbances and associated disruptions of radio communications based on the findings of solar events. These centres were usually located at institutes engaged in observations of solar activity and received reports from other solar and geophysical observatories. They exchanged telegrams about all "solar news" every day. Proceeding from the sufficiently complete available information, each centre gave a forecast for the radio service of its country.

If a centre expected an interesting phenomenon that ought to be observed globally, it reported to the World Forecasting Centre in Washington. If permission was received, it announced a "Geo-alert", which is a scientific alert for geophysicists of all countries.

Telegrams with this code word flew to all the observatories of the world. They contained brief information about any disturbance on the sun, a magnetic storm, the appearance of auroras, or a sudden warming-up in the stratosphere. The Geo-alert alerts all observatories and calls upon the scientists to conduct observations in accord with special programmes.

An Australian astronomer meeting the rising sun notices that a solar flare is imminent. The sun moves westwards and astronomers of different countries pose cautious questions to it. Telegrams about every thing detected come in to regional centres over the teletype network of a Special Warning Service and thence to the World Forecasting Centre of the IQSY in Washington. Signals come in from Irkutsk, from Delhi, as the flare bursts forth. Confirmation comes from the Capetown Observatory and from Sacramento Peak, New Mexico.

The "Alert" goes out over the teletype network from Washington—first to the centres of the large regions into which our planet is divided. These include the Soviet Eurasian Warning Service Centre at Krasnaya Pakhra, near Moscow. The news is then transmitted from the regional centres to all stations and observatories in every continent.

Alert! The Crimean Astrophysical Observatory obeys and turns its huge tower to film the brilliant disk of the sun. The same signal alerts the ionosphere specialist in the Peruvian Cordillera Range and he looks intently into the screen of his instrument. The alert tells the Yakutsk cosmic-ray investigator to launch a pilot-balloon with particle counters into the dull Arctic sky. Aurora stations in the Arctic and Antarctic switch their cameras to high-speed photography.

That is how the nerve lines of the IQSY Warning Service brought into action the huge army of researchers at two thousand stations strewn round the globe.

The programme of the International Quiet Sun

Year included studies of the sun and of such phenomena on the earth and in circumterrestrial and interplanetary space that more or less clearly exhibit a relationship with the sun. These phenomena are wide in range including the magnetic field of the earth, the auroras, the layer of atmosphere that reflects radio waves (ionosphere), cosmic radiation, and meteorological effects in the upper atmosphere. IQSY researchers attempted to decipher the peculiarities of these phenomena during the period of minimum solar activity. Later on we shall relate what scientists know about each of them and what they hope to find out after processing and analyzing the materials of the International Quiet Sun Year.

We live on an enormous magnet

We live on an enormous magnet and though we do not feel anything in particular, we are largely dependent on its behaviour. The human sense organs are deaf and blind to this phenomenon, but instruments tell us that terrestrial magnetism exists.

Ancient navigators had not the slightest conception of earth magnetism but they used the compass and made the magnetic field of the earth guide the compass needle and thus serve man.

No one knows who invented the compass and when, and what the first instrument looked like. At one time the opinion was current that the compass was known in the East in remote antiquity, thousands of years ago, or at least several hundreds of years before the Christian Era. How-

ever, more or less reliable information that the compass needle was capable of lying in a north-south direction refers only to the eleventh century A.D. It was also frequently asserted (though erroneously) that in Europe the compass was invented by the Italian Flavio Gioja in 1302. Some findings suggest that the compass, and a rather perfected version at that, was in use in Europe at the end of the 11th century.

The compass played an exclusive role in the great geographic discoveries. Quite right was the noted mathematician, shipbuilder and compass specialist Academician A. N. Krylov when he said: "Small though the compass is, America would not have been discovered without it."

It was originally believed that the compass needle points true north. Later it was noticed that the direction of the compass needle does not coincide at all places with the direction of the geographic meridian, but deviates from it by an angle that differs in various places. Thus, before Columbus sailed to the New World, people already knew of the existence of magnetic declination, the discovery of which for a long time was attributed by legend to this great navigator.

In 1576 the English seaman and compass master Robert Norman found that a freely suspended and completely balanced magnetic needle settles at a definite angle to the horizon. He built an "inclinator" or "inclination circle" that permitted measuring the slope angle of the force lines of the magnetic field relative to the horizon.

But about 200 years passed before magnetologists learned to perform relative measurements of the horizontal intensity of the magnetic field by

correlating the oscillation period of the compass needle at different places. It was only in 1832 that the great German mathematician Karl Gauss with the aid of Wilhelm Weber constructed the first magnetometer for measuring the absolute magnitude of the horizontal component of the magnetic field in the absolute system of units. Gauss also perfected instruments for observing variations of the magnetic field. All this work formed the basis for a comprehensive study of the great magnet of the earth.

In the Middle Ages and even later there were all kinds of absurd conceptions about the properties of magnets. For instance, it was thought that a magnet could lose its properties in the presence of garlic; and that dipping it in goat's blood could restore them. The ability of a compass needle to indicate north with one of its ends (poles) was explained either by the attraction of magnetic mountains or islands, or by a magnet hidden under the pole star.

At last, in 1600, the English physician and physicist William Gilbert published in Latin his famous work *Magnetism and Magnetic Bodies*. (*De Magnete, Magneticisque Corporibus*). It was the result of 18 years of experiments with magnets. The book gave a description of the properties of magnets found in numerous and extremely ingenious experiments and listed a few isolated facts about the distribution of magnetic forces of the earth.

Gilbert devoted great pains to experimenting with magnetized needles and studied the properties of a spherical magnet cut out of magnetite to which he gave the name *terrella* (or small earth).

His conclusion was exceedingly bold for the times: that there is magnetic strength in the earth and that the earth is a large magnet. These statements were later to form the basis of the science of terrestrial magnetism. His book was the first modern scientific treatise based on facts obtained from experiments and observations and not on scholastic, metaphysical discourse.

True, not all that Gilbert described in his book fits modern conceptions about terrestrial magnetism. For one thing, he believed that magnetic declination can change only at the boundaries of continents because of the differences in the magnetic properties of the ocean bottom and the land. In the middle of the oceans and in the centre of the continents the magnetic declination should, he said, not vary with change of place.

One hundred years later, in 1698-1700, the English astronomer Edmund Halley determined the magnetic declination in the Atlantic and published his *New and Correct Chart Showing the Variations of the Compass in the Western and Southern Oceans*, which clearly demonstrated that Gilbert's assertion was not true to fact.

In Gilbert's day, no variations of the magnetic field faster than secular change were known. Daily variations of magnetic declination were discovered in 1722 by the English instrument master Graham. A colleague of Celsius, known for his invention of the centigrade temperature scale, the Swede O. P. Hiorter carried out many-year observations of the behaviour of a magnetic needle and established a relationship between the rapid and irregular variations of magnetic declination and the aurora borealis.

Gilbert was also of the opinion that the magnetic declination of every place was a constant. But 35 years later Professor Henry Gellibrand, astronomer, determined the declination at London Bridge and compared the results with measurements carried out at the same spot on the Thames 12 and 54 years before him. He found that the magnetic declination in London had diminished from 11° to 4° in 50 years. That is how secular variations of the magnetic field were discovered.

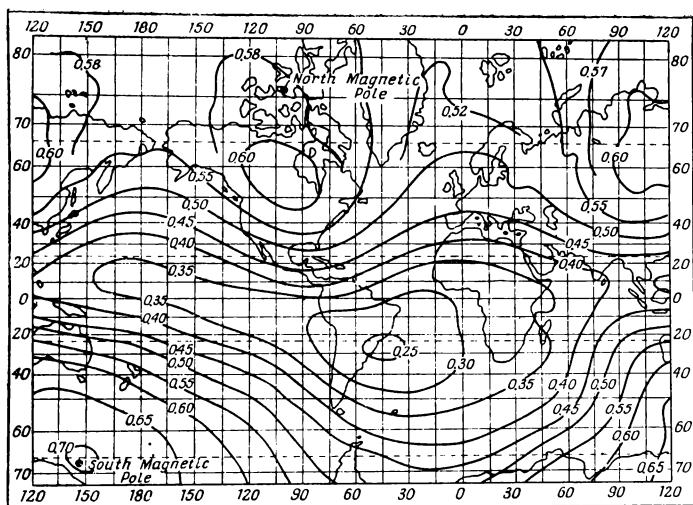
Gilbert believed that the magnetic axis of the earth coincided with its axis of rotation. But this did not prove to be correct. The magnetic axis of our big magnet is inclined to the rotation axis of the earth at an angle of roughly 11.5° and does not pass through the centre of the earth: it is displaced about 300 kilometres in the direction of the Caroline Islands. Thus, the "ends" of the geomagnetic axis—the geomagnetic poles—are over 1,200 km from the geographic poles. The direction of magnetization of this huge magnet of ours is such that the true north magnetic pole, from which the lines of force issue, lies in the southern hemisphere, while the true south pole lies in the northern hemisphere.

An analysis of the magnetic field has shown that the greater part of it, at least 99 per cent, is produced (just as Gilbert believed) by sources lying inside our planet. This basic portion is called the internal field. Its variations are secular in character. Unlike the internal field, the exterior field comprising 1 per cent experiences constant rapid variations, called diurnal variations, and magnetic storms.

The magnetic moment of the enormous magnet on which we live is expressed by what would seem to be a very impressive number containing 24 zeros. But one has to take into account the immense size of the magnet (the mean radius of the earth, it will be recalled, comes out to about 6,370 km). It then turns out that the intensity of magnetization of the earth (considering all parts as having the same magnetization) amounts to only 0.08 CGS units. Today, man has learned to make artificial magnets with intensities hundreds of thousands and millions of times greater. There is nothing remarkable in the fact that with such feeble magnetization the magnitude of the magnetic field of the earth is only 0.6-0.7 oersted at the magnetic poles, whereas at the magnetic equator it is half that value.

The internal field is conventionally divided into a field of homogeneous magnetization and a field of magnetic anomalies, the former making up about 85 per cent of the entire magnetic field of the earth. That is why we can roughly liken the earth's magnetic field to the field of a uniformly magnetized sphere, particularly when speaking of large distances from the centre of the earth.

The earth has numberless magnetic anomalies. The largest ones are called world anomalies: these include such giants as those in Eastern Siberia, North America and the southern part of the Atlantic Ocean. Smaller anomalies go by the name of regional. Finally, we have really small ones that are called local anomalies, the most famous of which is the Kursk magnetic anomaly caused by great deposits of magnetic ores. The



Distribution of total magnetic-field intensity over earth's surface in 1945 (in oersteds)

magnetic-field intensity here is roughly three times that at the magnetic poles of the earth.

The north (actually, the south) pole of the field of homogeneous magnetization (it is called the geomagnetic pole) is located near the Canadian polar station Alert at a point with co-ordinates 80.1° north latitude and 82.7° west longitude in the Arctic Archipelago of Canada, on the ice-covered island of Ellesmere, and the south (really, the north) pole lies in the region of the Soviet Antarctic station Vostok with co-ordinates 76.3° south latitude and 121.2° east longitude.

If the magnetic field of the earth were only

a field of homogeneous magnetization, the geomagnetic poles would also be the magnetic poles: that is, places where a magnetic needle freely rotating about its centre of gravity would settle in a vertical position.

But since magnetic anomalies interfere, the magnetic and geomagnetic poles do not coincide. By a 1962 determination, the north magnetic pole lies on Bathurst Island, near the Canadian polar station of Resolute Bay. Its co-ordinates are 75° north latitude and 100° west longitude. The south pole, also determined in 1962, lies near Commonwealth Bay (Antarctica) at 67° south latitude, 142° east longitude not far from the French scientific observatory of Dumont D'Urville.

Incidentally, by the time this book gets to its readers the poles may no longer be there because the magnetic poles depend on secular variations of the magnetic field in the region of the poles and also on the diurnal variations and on the magnetic disturbances created by the exterior magnetic field.

The position of the geomagnetic poles is determined by a mathematical analysis of the distribution of the magnetic field on the earth's surface according to a method developed and first realized in 1838 by the great German mathematician Gauss. But to determine the magnetic poles, one requires direct measurements of the magnetic field in their vicinity.

Attempts to determine the location of the magnetic poles were begun long ago. Theoreticians determined the co-ordinates of the north magnetic pole on the basis of observations of declina-

tion at widely separated places in medium latitudes. But the only thing they could agree upon was that it is located to the north of the Arctic Circle between Greenland and Alaska. Explorers spent decades trying to reach this remarkable spot, but all attempts failed.

In the first quarter of the nineteenth century, the Englishman William Parry and the American John Franklin, while searching for a north-west sea passage along the northern shores of America, carried out magnetic measurements and spared no effort to reach the coveted point. On one of these expeditions, Franklin and his comrades perished.

Though the magnetic pole was not reached, their observations helped to narrow down the region of the mysterious meeting point of the magnetic meridians. And Professor W. H. Barlow, a theoretician who had never been in this area, was able to determine the position of the magnetic pole on the basis of fresh data obtained from sites close to the pole. He placed it close to where it was found several years later by the Scottish polar explorer James Clark Ross.

Participating in a sleigh expedition in search of a north-west passage, with great difficulty he reached Cape Adelaide region on the coast of Boothia Peninsula, which juts way out into the waters of the Arctic Ocean on the Canadian coast.

He carried out magnetic observations here on June 2, 1831, and finally found the spot or, rather, the region where the north magnetic pole was then situated and where the inclinometer needle stood up vertically. Needle inclinometers were so imperfect in those days that one could not speak

of an exact determination of the position of the magnetic pole. Ross felt "hurt" that a place so important to science should have been left unmarked by nature and so commemorated it with a small pile of rocks.

The next scientist to visit these uninviting wastes and try to determine the site of the north magnetic pole was the great Norwegian polar explorer Roald Amundsen. In 1903-1906 he and six companions in a small ship sailed westwards from Greenland to Alaska.

In May 1904 they reached the region of King William Island by dog-sled and established that the magnetic pole had "moved" some sixty-five kilometres from the spot indicated by Ross. Amundsen did not confine himself to a brief visit; 250 kilometres away at Petersen Bay, where he had to halt, he set up a magnetic observatory Gjoa Haven, where the wintering party recorded magnetic variations during 19 months.

This first long-term recording of variations of the magnetic field near the magnetic pole brought to light that the declination can change here during magnetic storms by hundreds of degrees. This is not because magnetic storms are particularly strong in the area but that the horizontal component which ordinarily holds the compass needle in the direction of the magnetic meridian is close to zero.

That is why the magnetic poles of the earth can, during diurnal variations of the exterior magnetic field, move tens of kilometres and even "run off" hundreds of kilometres during magnetic storms. From this it is clear that any determination of the positions of the magnetic poles

to within minutes or, all the more so, seconds of latitude and longitude is physically meaningless. The magnetic poles of the earth are constantly in motion.

But time passed and with the demand for increasingly exact magnetic determinations came improved instruments for scientific observations and transportation facilities for the geophysicists. A virtual assault was made on the Far North. Frenchmen, Canadians, Americans, Danes, Englishmen and again Canadians pushed by ship and dog-sled and by aerosleigh and skis to many near-inaccessible regions. Magnetic measurements were conducted over vast areas from Greenland to Alaska.

Soviet scientists also carried out a large number of magnetic measurements in the Arctic.

In this work of determining the magnetic pole in the Central Basin of the Arctic Ocean, a very important role was played by the Soviet "North Pole" drifting station. For the first time in history, in May 1937, four Soviet polar explorers were dropped onto an ice-floe near the point of the geographic North Pole. For nine months they fought the rigours of Arctic nature and studied one of the largest blank spots on the map of the world. During these 274 heroic days the expedition collected far more scientific material than any polar expedition of the past.

Of particular significance were the observations of the earth's magnetic pole conducted during the drift by the young magnetologist E. K. Fyodorov. These observations were conducted over a range of 2,500 km of drift and greatly refined scientific conceptions about the state of the geomagnetic

field near the geographic pole of the earth and towards the magnetic pole.

Since that time the setting up of drifting stations for studying magnetic, meteorological, hydrological and other geophysical phenomena has become a tradition. The example of the Soviet Union was followed by the United States, which during the IGY organized the drifting stations "Alfa" and "Bravo". During the IQSY, the Soviet Union had two drifting stations in the middle of the Arctic, "North Pole 12" and "North Pole 13". On land too, we find more and more air-supplied "jumping" expeditions like the Soviet annual expeditions "Sever" (North) and the Canadian explorations of the Arctic by aircraft, which were begun in the late 1940s by the Dominion Observatory at Ottawa.

Finally, an attack was made on the other blank spot of the globe, the Antarctic. One of the first to attempt a determination of the south magnetic pole was that indefatigable polar explorer of the 19th century James Clark Ross. Ten years after the discovery of the north magnetic pole he came comparatively close to the south magnetic pole, but was not able to determine its exact position.

Robert Scott, the outstanding English polar explorer who later heroically perished on a wind-swept plateau of ice, was the first to reach the vicinity of the south magnetic pole. In 1903 he determined the position of this remarkable point with co-ordinates $72^{\circ}45'$ south latitude, $156^{\circ}22'$ east longitude.

Several other polar explorers made subsequent determinations of the position of the south mag-

netic pole. Among them were the remarkable observations of the geophysicist Prof. David, a member of the British Antarctic expedition headed by the famous polar explorer Ernest Shackleton. In January 1909 David "caught" the magnetic pole 2,500 km from the geographic pole, deep within the Oates Coast at 72° south latitude, 155° east longitude.

One of the most recent determinations right at the pole itself was made in 1952 by a French polar expedition that found the pole at about $68^{\circ}40'$ south latitude, 143° east longitude. And just before commencement of the IGY, in 1955, the south magnetic pole was located in the upper reaches of the Mertz Glacier (68° south latitude, 144° east longitude). Thus, in 45 years it ran a distance of over 600 km.

It is interesting to note that the movements of the north and south magnetic poles are not coordinated. This suggests that what we have is not the motion of an imaginary magnetic axis, but local secular variations in the regions of the magnetic poles.

But why are the magnetic poles wandering? Where does the internal magnetic field of the earth come from and whence are these secular variations? Many scientists, since the time of Gilbert, have attempted to unravel this riddle, but without success. The search is still on.

At one time scientists were inclined to think that magnetism is the property of all large bodies in rotation. During the past 15 or so years other possibilities have been studied to account for the internal magnetic field of the earth by taking into consideration peculiarities of the internal struc-

ture of the planet, which to a large extent are rather obscure.

It is presumed that the inner solid core of the earth is in a special metallic state and for this reason possesses a high electrical conductivity despite the great temperature in the interior. The core rotates at a speed somewhat different from that of its fluid shell. The result is that eddy-type motions are set up within it. Apparently, the core of the earth acquired a certain initial magnetization. Whether this is due to rotation or to the action of some exterior magnetic field is not clear. Because of eddy motions of the conducting masses of the shell of the core relative to the magnetic field of the core, electric currents are set up (like those in the windings of a dynamo), whose magnetic field builds up the initial magnetic field of the core.

This process of self-excitation continues until an equilibrium is established in which the energy lost due to dissipation of heat generated by the currents is balanced by the mechanical energy expended on generating eddies in the core's shell.

An interesting thing is that space vehicles can play an important part in verifying such "inner-terrestrial" laws as the theories of magnetism. The point is that artificial satellites and space probes have made geophysical experiments possible for the first time, and without experiments and comparisons no science can exist today.

Here is the way scientists reasoned. The earth has an inner core and a magnetic field. A variety of features suggest that Mars and Venus should also have inner cores, while the moon should be lacking (or almost lacking) one. The problem

therefore was to find out whether they had magnetic fields.

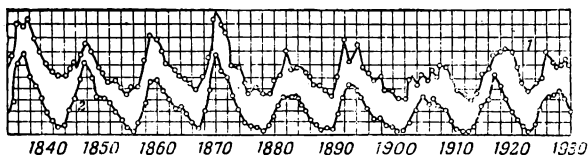
The Soviet space probe Luna 2 was fired moonwards, and careful measurements by extremely sensitive apparatus at distances up to 50 km from the lunar surface indicated that the moon has no magnetic field, at least it was not perceptible.

So far attempts to measure the magnetic fields of Mars and Venus have been less successful. But sooner or later this will definitely be accomplished and then scientists will be in a better position to judge about our own magnetic field.

At the end of the eighteenth and the beginning of the nineteenth century, interest in studies of terrestrial magnetism was very great. On the initiative of Alexander Humboldt, the great German naturalist, a network of magnetic observatories was set up in Europe and, later, on the other continents. Here systematic observations of magnetic-field variations were conducted. Between 1836 and 1846, the whole network co-ordinated their scientific observations on the basis of a unified programme. This was the first case of international co-operation of scientists studying the earth and it went down in history under the name of the Magnetisches Verein. Russian observatories at St. Petersburg, Ekaterinburg (now Sverdlovsk), Barnaul and Nerchinsk also participated.

The work was arduous, for photographic recordings were not yet known and the scientific workers had to spend hours on a stretch at their instruments taking down readings every 5 minutes.

This many-year effort was a great success; it was found that variations of the earth's magnetic



Lower curve (2) indicates variation of solar activity. The earth's magnetic field (1) follows closely in step. True, in some cycles maximum magnetic activity can set in somewhat later than maximum solar activity

field are somehow connected with the variation in number and dimensions of sunspots. The Austrian scientist J. Lamont noted this relationship in the way the amplitude of diurnal variations of magnetic declination fluctuates with the solar cycle. The British magnetologist E. Sabine found the same relation from solar activity coinciding with the frequency and intensity of magnetic storms. Another English researcher, Brown, detected the tendency of magnetic storms to recur roughly every 27 days, which is approximately the time it takes the sun to complete one rotation on its axis if we make allowance for the earth's motion about the sun. The discovery of a connection between solar phenomena and magnetic events stimulated the search for relationships between solar and other geophysical phenomena. That is how the great problem of sun-earth relations, which today concerns many thousands of scientists, was born.

Today, all magnetic observatories of the world conduct round-the-clock photographic registration of variations of the magnetic field. Special instruments—magnetographs—also record the

magnetic declination and two (horizontal and vertical) components of the total magnetic-field intensity.

Magnetograms (which is the name given to traces of the magnetic pulse of our planet) note every single variation. There are days when they exhibit clear-cut regular variations with a period equal to the solar day. Such days are termed magnetically quiet days. Variations like these are particularly characteristic of the lower latitudes and are most frequent when the sun is at lowest activity.

During the years of maximum solar activity, diurnal amplitudes of differences between greatest and least values in diurnal variations come out 60 per cent greater than at times when the sun is quiet. Generally speaking, the magnetic field changes more in the summer than in winter and more in the daytime than at night. On magnetically quiet days, all these variations are more or less regular and orderly.

But there are times when the pulse of the earth jumps out of its regular variations and becomes rapid and irregular. This is a magnetic disturbance. If the disturbance is considerable and the magnetogram displays large zigzags, it may be called a magnetic storm.

Storms in the magnetic field of the earth are most frequent when the sun is close to maximum activity, and are strongest in the higher latitudes, particularly in the Arctic and Antarctic that have frequent auroral displays. Still, even in the polar regions and even in the most intense magnetic storm the magnitude of magnetic disturbance never exceeds several per cent of the constant mag-

netic field. Thus, despite a certain change of moods, the magnetic temperament of this planet may be taken as rather balanced.

In scale, magnetic storms are divided into world-wide that embrace the whole planet and persist for a number of days, and polar, which occur only in the higher and medium latitudes and in the course of a few hours.

There is yet another phenomenon that has attracted attention since it was first detected at the end of last century when new and more sensitive instruments were designed. It consists of rapid and rather regular variations of the magnetic field with periods of a few minutes or less. They go by the name of magnetic micropulsations and occur at all times, no matter what the mood of the magnetic field, quiet or excited. Some are recorded simultaneously even by observatories separated by large distances, others (the most intense ones) are real giant pulsations that appear only in comparatively limited regions near the auroral zone.

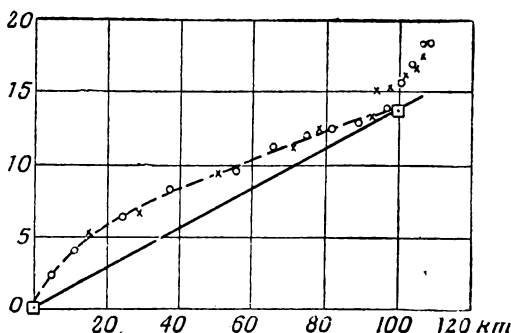
Where does all this regular and irregular ebbing and flowing in the magnetic sphere stem from? Mathematical methods of analysis have come to the aid of geophysicists. They suggest that most of the diurnal variations and magnetic storms are generated by external sources lying outside the solid body of the earth, and only about one-third originate within our planet.

As for variations of an internal origin, there is no doubt that they are produced by currents induced in the upper electrically conducting layers of the earth by variations in its exterior magnetic field.

Diurnal changes in the magnetic field are accounted for most realistically by the "atmospheric dynamo" hypothesis advanced at the end of last century by the English investigator Arthur Schuster and developed in more detail by Sidney Chapman, also of England. According to this theory, the quiescent diurnal variations are due to electric currents in the ionosphere, which is an atmospheric layer roughly 60 km above the earth's surface. It differs from the lower-lying layers in that it contains large quantities of charged particles, ions and electrons. Quiescent diurnal variations occur when the ionosphere moves in the magnetic field of the earth and responds (like the world ocean) to the tidal forces of the sun and moon and to temperature variations. In a word, then, the magnetic field of the earth is a "permanent magnet", the atmosphere is the "armature" and its conducting layers the "winding" of a gigantic "dynamo", in the middle of which we live.

Ionization of the upper layers of the atmosphere (the formation here of large quantities of ions and electrons) is due to the action of the sun's ultraviolet and X-radiations. The ionization and, hence, electric conductivity of the upper atmosphere over every spot varies with the time of day, the season of the year, and the cycle of solar activity. Also connected with this factor are the diurnal variations of the magnetic field mentioned above.

Though this scheme accounted for very many phenomena it remained a hypothesis until instrument-carrying rockets made possible magnetic measurements at high altitudes. Scientists could then make direct "contact" with all these events.



This is how the magnetic field near the geomagnetic equator diminishes with altitude. These rocket measurements were made in the vicinity of a local anomaly, so actual reductions (open circles) differ from the theoretically calculated values (solid line)

The first direct high-altitude measurements were obtained in the region of the geomagnetic equator. Theoretical calculations show that the earth's magnetic field should diminish gradually with altitude, exhibiting no abrupt changes. However, rocket tests disclosed two breaks in this theoretically calculated decrease of field with increasing altitude: in a zone 93 to 105 km up. The results were the same both in ascent and descent.

This sharp jump in magnetic-field values indicated an additional magnetic field in this zone set up by currents in the ionosphere. At Fort Churchill (Canadian polar station), a rocket was launched during an auroral display and it too detected the existence of currents in the ionosphere.

So far there have not been many experiments of this kind, and not every one has been a suc-

cess. In some cases such discontinuities in the magnetic field were observed at altitudes of 100 and 110 km, and once the rocket reached a height of 120 km but had not yet emerged from the current-carrying layer.

The most spectacular display in the magnetic arsenal of the earth are world-wide magnetic storms. Specialists are prone to say that during the hundred or so years that magnetic storms have been recorded, no two have been exactly alike. Try to classify them and construct a theory of such a phenomenon!

Still and all, many storms have a number of common peculiarities. Most of them commence imperceptibly and gradually, so that it is impossible to state exactly when the magnetic weather went foul. On the contrary, the ones that commence suddenly exhibit small but abrupt changes of the magnetic elements that are recorded at practically one and the same time at widely separated observatories.

Magnetic storms also terminate in a very peculiar manner. After the principal fluctuations of the magnetic field cease, the field gradually settles down into its normal state. The process is rather rapid at first but then slows down spreading over many days. These post-disturbances are best studied during minimum solar activity when there is a long period of magnetic calm between storms.

Polar storms are another kind of disturbance in which the uneasy nature of the magnetic field is manifested. Unlike the world-wide storms, they embrace mainly the Arctic and Antarctic and adjacent regions, are of shorter duration, usually

not more than a few hours, and are more intense on the night (unilluminated) side of the earth.

The year was 1918, Europe was still in the grips of World War One. But even during these trying years of destruction, man did not give up creative effort completely. At the Potsdam Observatory, the German scientist Adolf Schmidt came to the conclusion that during magnetic storms a ring of electric current can develop about the earth flowing constantly from east to west.

The magnetic field of a ring current of this kind should diminish the horizontal component of the magnetic field whenever the principal phase of a storm is in progress. At the end of the phase, the ring current falls off in strength and creates the effect of a gradual calming down, which is what we actually observe.

Schmidt did not say at what distance from the earth these currents circulate. And those scientists that did could not come to any agreement. The Norwegian Carl Störmer considered that they could be a hundred earth radii from the surface, while Sidney Chapman, just as much of an authority, maintained that the distance was only a few radii. The disparity is quite natural for we know too little about the immediate vicinity of the earth.

There is still no unified and generally accepted theory of magnetic disturbances, although many outstanding workers have attacked the problem. There are hypotheses galore, but they would take us too far afield. We shall only go into the basic ideas of two of them that not only have to do with explaining magnetic storms but are intimately bound up with auroras and cosmic rays.

The relationship, long since known, between magnetic disturbances and the auroras suggested that all magnetic-field variations and the Northern Lights are caused by charged particles ejected from active regions of the sun and captured by the field of the magnet on which we all live.

This problem was taken up at the same time but from different angles by two Norwegian scientists. Kristian Birkeland, an experimenter par excellence, recalled the childhood of geomagnetism and, like Gilbert, reverted once again to the toy earth, the terrella sphere, this time not one of ironstone but in the form of a spherical electromagnet. He placed his model of the earth in a large vacuum chamber about the volume of a cubic metre and irradiated it with electrons. So as to be able to see the pathways of the rays, Birkeland coated the terrella with a phosphorescent material and in various places on it mounted ingeniously designed phosphorescent screens.

In numerous experiments he demonstrated that in all cases when magnetization of the terrella exceeded a certain level, dependent on the velocity of the cathode rays, they could bombard the terrella in only two zones: near the magnetic poles. The luminescence of the terrella due to bombardment with cathode rays was in the form of isolated spots in certain cases and spirals about the magnetic poles, in others.

Birkeland also found that the cathode rays could even circle the terrella a number of times before coming down to its surface. In certain cases they moved from one pole to the other. The favourite point of impact of the cathode-ray par-

ticles was the side opposite the sun, that is, away from the cathode ejecting the electrons (the night side of the terrella). That is how the chief peculiarities of auroras were reproduced in the laboratory.

A drawback in Birkeland's experiments was that they did not enable one to judge about the trajectories of motion of the separate particles in the magnetic field of the terrella. Another Norwegian, the physicist and mathematician Störmer, worked enthusiastically for many years over theoretical calculations of the trajectories of individual particles entering the magnetic field of the earth. All manner of orbits came out of his pencil point. There were open trajectories, nearly circular, lying in the plane of the magnetic equator, in which swarms of electrons embrace a greater or smaller part of the planet in a west-to-east direction, but do not become satellites.

Störmer conjectured that it was these particles that build up during magnetic storms. Then the magnetic forces of the particles should combine at distances of a hundred earth radii, which is beyond the moon's orbit, forming a belt of currents flowing from east to west.

Birkeland's experiments, which were repeated by many investigators using more refined devices yielding very narrow electron beams, and the calculations of Störmer formed the basis of a theory of magnetic storms and polar auroras that bears their names. The experiments did not only agree with calculations, but predicted the existence of particle motions that were actually found only half a century later during the IGY, when

Soviet and American scientists discovered belts of radiation surrounding the earth.

The Norwegian scientists maintained that the auroras are caused by luminescence of the air due to the influx of charged particles into the upper rarefied layers of the earth's atmosphere, while magnetic storms result from the direct action of the magnetic field of these moving particles.

But how are we to account for the great variations of the field which occur during magnetic storms? The point is that the particle flux must be very dense for this purpose. And the army of particles spewed out by the sun should "quarrel" en route, for particles of the same sign would set up repulsive forces and disperse.

The Birkeland-Störmer theory was not able to overcome this contradiction. Their explanation of magnetic phenomena was at loose ends, but it functions very well in accounting for high-energy particles of low density, such as, for example, cosmic rays moving in the magnetic field of the earth.

About thirty years ago, the English scientists Chapman and Ferraro advanced a theory of magnetic disturbances and auroras. They believed that the sun emits neutral streams of ionized gases—plasma—consisting of an equal number of charged particles of opposite sign. Measurements of the time lapse between a solar flare and the onset of a magnetic storm on the earth indicate that the mean velocity of cosmic particles ejected by the sun and presaging a storm should be about 1,500 km/s.

Imagine holding a water hose; the water is spouting out and you begin to rotate about your

axis. The drops of water coming out of the hose continue in rectilinear motion but the stream as a whole begins to curve as you turn.

That is what happens to particles coming out of the sun, according to Chapman and Ferraro. The curvilinear corpuscular stream caused by the sun's rotation reaches the earth and showers its magnetic field from the night side. In the process, electric currents should be induced on the side of the electric-conducting stream facing the earth; the magnetic field of the currents combines with that of the earth and enhances it in the space between the stream and the earth. Inside the stream, on the contrary, the field is weakened. The result is a sort of compression of the earth's magnetic field. This is recorded in observatories as the first phase of a magnetic storm typifying a build-up of the horizontal component of the field.

The solar "forces" encounter resistance of the "earth-dwellers"—the magnetic force lines of our planet try not to allow particles to reach the earth. The stream of solar gas compresses the force lines of the field and begins to flow round the pocket of resistance, producing a sort of spherical indentation in the cloud of sun-delivered plasma.

While the solar army is circling the earth, some of the invaders are taken prisoner: certain particles are captured by the force lines of the magnetic field and are forced to revolve round the earth forming a ring current. This whirling persists even when the invasion is over and the earth emerges from the stream. But the intensity of the ring current gradually falls off with time.

The principal phase of a magnetic storm on

the earth is observed precisely at the peak of such a merry-go-round; it then diminishes and the field gradually reverts to its normal state.

But how is a ring current formed? Where do the auroras come from? These questions are connected because the theory of magnetic storms is closely bound up with the theory of auroral displays. To this there was no answer.

At what distances from us do these events occur? This wasn't quite clear either, although Chapman believed that the electric current developed somewhere between three and five earth radii from the centre of the earth.

On the eve of the IGY, an American physicist S. Fred Singer put forth a new and extremely fruitful idea. His supposition was that currents responsible for the principal phase of magnetic storms are generated by particles captured by the earth's magnetic field. Such particles should revolve about the earth and at the same time slip along spiral paths round the force lines of the magnetic field from one hemisphere to the other and back again.

Since electrons would be moving round the earth eastwards, and protons westwards, the result would be a current in the westerly direction. But then it would have the shape not of a circle lying in the plane of the magnetic equator, but of a whole current stratum, a current belt embracing practically the whole earth from one magnetic pole to the other.

This layer of current would follow the force lines of the magnetic field; it would come closest to the earth at the magnetic poles and be farthest away at the magnetic equator. The most intense

current flows near the equator; and protons are the most effective particles producing it. Some of these particles could penetrate into the upper atmosphere and generate polar auroras.

Subsequent observations of natural particles in the radiation belts of the earth (which were discovered during the IGY) and of artificial radiation produced in atomic bomb explosions at high altitudes fully confirmed the type of particle motion predicted by Singer. That is why all modern theories of magnetic storms, including the renovated theory advanced in recent years by Chapman and his pupil the Japanese scientist Syun-Ichi Akasofu, proceed from the fact that a current layer is generated during magnetic storms.

All this was only hypothesis, though a very likely one. How could we verify the existence of such an extra-ionospheric layer? And establish its distance from the earth? One had to find a direct method for establishing the fact that circumterrestrial space really had charged particles and in sufficient quantities and that the geomagnetic pole changes with increasing distance from the earth not in accord with the law that follows from the mathematical theory of terrestrial magnetism proposed by Gauss.

The only way to verify this hypothesis was to send aloft space vehicles: rockets and satellites with magnetometers and a variety of charged-particle counters. They would make the measurements and telemeter them back to earth.

Studies of the field and particles via satellites and rockets that were begun during the IGY constituted a significant segment of the IQSY programme. They drastically changed our conception

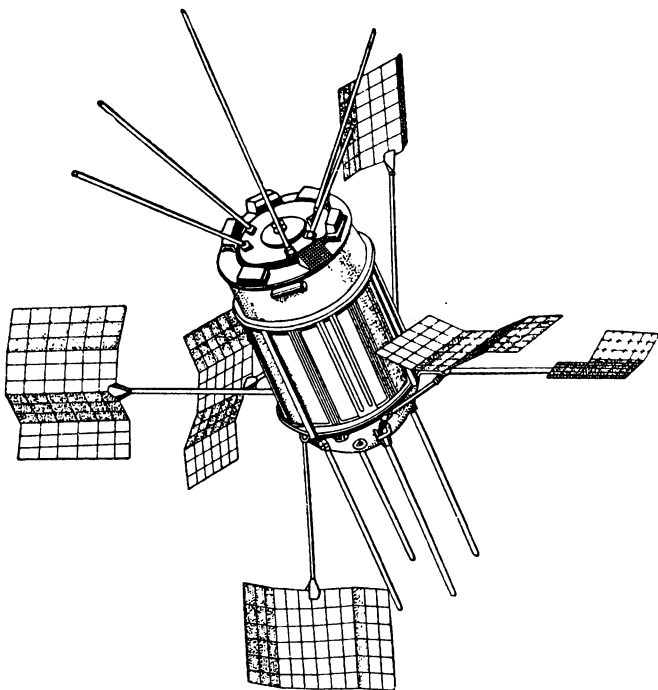
of the space about the earth and about the structure of the magnetic field at large distances.

Although investigations of the field and particles are closely bound up and the results of one cannot be grasped without the other, we shall nevertheless examine in more detail only the magnetic studies. Particles will be taken up in the chapter "The Invisible Belts of the Earth".

The first experimental indications of the possible existence of an extra-ionospheric current layer were obtained during the flight of the Soviet space rocket Luna 1. It was launched moonwards on January 12, 1959, and, passing at about 5 to 6 thousand kilometres from the moon, became the first man-made planet of our solar system.

When the probe had receded to from two to five earth radii from the centre of the earth, the magnetometer on board noted a substantial decrease in the field intensity compared with what should have been expected on the basis of Gauss' theory for the case when all field sources lie inside the earth. At the same time, charged-particle counters recorded accumulations of high-energy electrons at these distances. The decrease in intensity of the magnetic field was interpreted as an indication of a current layer.

Similar results at about the same distance were obtained by Luna 2 which was launched on September 12, 1959. The American satellite Explorer 6, in August-September 1959, repeated measurements of the magnetic field at distances from two to eight earth radii both during the quiescent state of the field and during magnetic storms.



Soviet Electron 2 space station

These measurements showed that there is a decrease in the field intensity at three to four earth radii from the centre of the earth both in quiet and excited fields. But during magnetic disturbances it becomes larger.

Important measurements of the magnetic field in this region of space were carried out during the IQSY by the Soviet space vehicle Electron 2.

Between January 30 and May 5, 1964, the satellite had two instruments functioning: one more sensitive than the other. This made measurements possible out to distances of 3 to 11.6 earth radii.

Long-term measurements of Electron 2 both on the outgoing and incoming branches of its trajectory established quite definitely that at distances from three to five or six earth radii the actually observed field is always less than the theoretically calculated field. On days of magnetic disturbances, the difference between observed and calculated fields increases considerably.

At still greater distances the observed field is more than the calculated one, and this difference ordinarily increases with the onset of a magnetic disturbance.

Unlike the Soviet investigators, their American colleagues focussed attention on elucidating the nature of the field that "resides" at a distance of about seven earth radii and more. Here, too, very interesting peculiarities were discovered. Explorer 6 and, later, Explorer 10 launched in March of 1961 demonstrated that the perturbing field, which makes the observed field different from the theoretically calculated one, is in a direction opposite that of the sun. The idea arose that this effect might be accounted for by the action of the solar wind.

A theoretical consideration of the interaction of the solar wind (solar plasma moving at supersonic speeds) with the earth's magnetic field, which was initiated by Chapman and Ferraro, led scientists to very interesting and, at first glance, quite exotic conclusions. It was found that the earth's magnetic field at large distances

should differ from the field of a uniformly magnetized sphere.

The field of uniform magnetization falls off the same way in all directions: in proportion to the cube of the distance from the centre of the earth. At two radii from the centre, it would be eight times weaker than at the earth's surface, at three radii, 27 times weaker, etc. And there would be no definite boundary line.

But if there is a constant solar wind, the earth's magnetic field would be limited to a certain region called the magnetosphere. The boundary of the magnetosphere—the magnetopause—would come closest to the earth at the subsolar point, that is, where the sun is in the zenith. On the morning or evening side of the earth, it would recede from our planet.

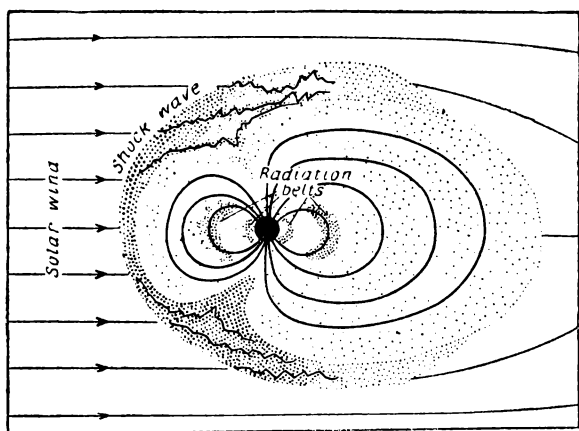
As to the location of the boundary on the night side, there are two different hypotheses: the open and the closed magnetosphere. The propounders of the open magnetosphere believe that part of the force lines of the magnetic field are broken and connected to the earth at one end only, the other end going off to astronomic distances. The noted American theoretician A. Dessler believes that the magnetosphere extends to distances of 20 to 50 astronomical units on the night side (the astronomical unit is the earth-sun distance).

Supporters of the closed magnetosphere picture it in the form of a gigantic drop, the elongated end of which may extend out to several tens of earth radii on the night side of the planet.

The magnetosphere is surrounded by a magnetic shell or intermediate region formed by the particles of the solar wind reflected from the

magnetosphere. Unlike the magnetosphere where the magnetic field is stable and regular, the field of the shell experiences constant variations in magnitude and direction due to numerous local eddies.

The configuration and behaviour of the magnetosphere depends on the properties of the solar wind interacting with it, its composition and the velocities of the constituent particles, the presence or absence in it of a magnetic field, on whether the stream is turbulent or eddy-free, and whether the solar wind is blowing smoothly or in gusts. In the absence of experimental data, the various authors proceeded from different conjectures about the solar plasma and its interaction with the magnetic field of the earth. Quite natu-



A model of the magnetosphere (cross-section). Black circle in centre represents the earth. Curves indicate magnetic lines of force

rally, they arrived at different models of the magnetosphere.

Today it is possible to obtain information about the solar wind and to choose between the different models of the magnetosphere. Space vehicles have been launched into very eccentric orbits that cut the magnetosphere and extend out beyond it and measure the corpuscular radiation and the magnetic field.

The Soviet and American interplanetary stations of the Luna, Mars, Venus, and Mariner series have, in their extended voyages, repeatedly entered streams of solar plasma and sent back information about it. The density has been found to vary from one to ten protons per cubic centimetre. Stream velocity may range from 300 to 700 km/s. Its magnetic field is rather weak, on the average about 5 gammas.

Very important data about phenomena at the boundary of the magnetic field have been obtained by the American space vehicles Explorer 12 and Explorer 18 and the Soviet vehicles Electron 2 and Electron 4 launched into very elongated orbits. Explorer 18, which also goes by the name IMP 1 (an acronym for Interplanetary Monitoring Platform), was designed mainly for measuring the interplanetary magnetic field. Its original apogee equalled 197,000 km. American satellites of this type are orbitally inclined about 30° and consequently yield information about events near the equatorial plane. Soviet Electron vehicles are launched into orbits inclined about 60° , thus covering phenomena in the higher latitudes.

Measurements made by Explorer 18 showed

that near the boundary of the magnetosphere, at distances exceeding seven earth radii, the observed field begins to depart from the theoretically calculated one and increases beyond the latter. The boundary of the magnetosphere in the subsolar point is at a distance of about ten earth radii. Here the observed field is roughly twice the theoretically calculated field.

In passing through the magnetopause, whose thickness varies between 1,000 and 5,000 km, the magnetic field falls off sharply and becomes unstable both in magnitude and direction. The intermediate region near the subsolar point comes to an end at about 13.4 earth radii. Beyond is the region of the interplanetary magnetic field.

The magnetic field of interplanetary space was shown by Explorer 18 measurements to be more stable than had been found in earlier measurements. For extended periods of time, the field intensity fluctuated but slightly—between 4 and 7 gammas.

The variability in direction was found to be significantly greater. Some scientists believe that the interplanetary field is of solar origin and is formed by magnetic-field lines stretched out by the solar wind and turned into something like a magnetic bottle.

It is presumed that the solar wind can carry force lines of the terrestrial magnetic field to the night side of the earth and extend the force lines that come out of the earth or enter it near the magnetic poles. Some geophysicists consider that certain force lines of the earth's magnetic field can be broken to form the open magnetic "tail" of the earth mentioned earlier.

Space measurements of the magnetic field and the distribution of charged particles gives us reliable information about the magnetic sphere of the earth. However, our knowledge of this region, which plays so important a role in regulating solar effects on the earth, is accumulating at a very slow rate. Most findings so far relate mainly to the day side of the earth. Little is known about the night side.

The enormous size of this region does not permit us to judge about events throughout its thickness on the basis of the flight of a single satellite. Recall that the orbital period of Explorer 18 was 93.5 hours and most of this time it was outside the magnetosphere. To obtain simultaneous synoptic data, measurements will have to be made by a system of satellites flying in different orbits and at various distances from the earth.

A step in this direction has been made by the launching of the Soviet Electron space vehicles.

Electron 1 and Electron 2 were launched on January 30, 1964, thus, as it were, ushering in the International Quiet Sun Year. These two satellites launched by a single powerful rocket comprised a unified system performing in a single experiment. The angle of inclination of their orbits to the plane of the earth's equator was about the same—close to $60^{\circ}50'$.

But Electron 2 was farther out with an apogee of nearly 11 earth radii (close to 68 thousand kilometres), while Electron 1 had an apogee of only 7,145 km. The orbital periods were, accordingly, 2 hours 49 minutes and 22 hours 36 minutes.

Why were these satellites put into such different orbits at the same time? Because this makes possible simultaneous measurements in different regions of circumterrestrial space.

So far very little information has been obtained about the movements of the boundary of the magnetosphere; we cannot say reliably just how stable this boundary is when gusts of solar wind bring about magnetic disturbances. Neither do we know how particles of the solar plasma enter the magnetosphere.

Some researchers suggest that the magnetosphere is poorly protected, all the time in motion and letting pass all kinds of "violators"—fluxes of solar particles. Others believe that the magnetosphere feeds on particles on the night side because its tail is open. Still others consider that particles of the solar plasma can penetrate into the magnetosphere in the region of the so-called neutral points where the magnetic field is very weak and might even be equal to zero.

All these differences have compelled scientists in different countries to seek a solution of the problem in laboratory experiments with the Gilbert and Birkeland terrella. But now they irradiate it with streams of neutral plasma and not with particles of one sign, in other words, just like the real sun irradiates the earth.

Some investigators have taken the earth (its model, that is) into the laboratory. Others have turned the entire planet into a laboratory. During the IQSY over 230 magnetic stations, including 26 Soviet stations scattered over the face of the globe, conducted round-the-clock observations of the magnetic "weather"

We know what significant conclusions have been drawn concerning the structure of the outer part of the earth's magnetic field on the basis of ground-based observations alone. Now that these are being supplemented with satellite observations, the value of the material is greatly enhanced.

At the beginning of the International Geophysical Year a network of observatories had been set up in the Antarctic. This made it possible, during the IQSY, to investigate the behaviour of the magnetic field in both polar regions at the same time. Particularly interesting were observations of the so-called conjugate points—the two opposite ends of one and the same line of force near the regions it “contacts” the earth.

It was found that near points lying under the zone of the auroras, the force lines connecting such conjugate points are distant from the earth's centre in the plane of the magnetic equator five to six earth radii. Magnetic disturbances not only begin in both hemispheres practically at the same time, but develop more or less in similar fashion. This is particularly evident during equinox when the subsolar point lies in the plane of the magnetic equator. In the case of conjugate points lying closer to the geomagnetic belts, the force lines of which points go out to greater distances from the earth, good agreement is observed only during polar storms and at nighttime.

Studies of phenomena that occur at conjugate points are of great interest. During the IQSY, cooperation among scientists conducting observations at these points was particularly close. The

Soviet Antarctic Observatory Vostok at the south geomagnetic pole and the U.S. station at Thule in Greenland at the north geomagnetic pole, the Canadian station Great Whale River on the shore of the Hudson Bay and the U.S. Byrd station in the Antarctic, our observation post at Sogra (Archangel Region) and the French subantarctic island Kerguelen in the Indian Ocean, and also many other conjugate points are all connected by unseen bonds, and every single geomagnetic event in one of these regions will be correlated with the utmost care with everything that took place at the opposite end of the world.

The secrets of sun-earth relations are being attacked from all sides. The magnetic sphere of the earth keeps a tight grip on its riddles, but the time is not far off when many of them will be resolved.

World-wide magnetic survey

The distribution of elements of the magnetic field over the earth's surface, particularly where there are magnetic anomalies, is very complicated. To establish its character in some part of the globe, whether on land or at sea, a magnetic survey has to be made; this amounts to determining the direction of the force lines of the field and the magnitude of the field at a large number of points more or less evenly distributed over the entire territory under investigation. The results of these measurements are usually plotted on special magnetic charts.

For studies of the structure of the earth's crust

and for prospecting purposes, maps of the total magnetic intensity or its vertical component are compiled; for navigational requirements of ships and aircraft, maps are compiled of the magnetic declination for determining the angle at which, for a given place, the compass needle departs from true north.

Magnetic charts may be more or less detailed. For example, when prospecting for minerals in areas of magnetic anomalies, measurements are sometimes made every few tens of metres. When compiling world-wide magnetic maps and charts for nautical and aerial navigation, measurements spaced by tens and even hundreds of kilometres may suffice.

Seafarers were the first to make practical use of the earth's magnetism for purposes of navigation. No wonder then that the world's first magnetic survey was made at sea. In 1698-1700 the English astronomer and geophysicist Edmund Halley, on the sloop *Paramour Pink* investigated the northern and southern parts of the Atlantic Ocean for this purpose. He compiled the first magnetic map in the world.

Magnetic surveys on land were begun much later. Even at the beginning of the twentieth century, considerable areas (vast regions of Africa, Asia, South America, to say nothing of the Arctic and the Antarctic) were still unsurveyed. Credit for wiping out these blank spots on the magnetic map of the world goes largely to the American magnetologists Louis Agricole Bauer and John Fleming. In 1904 they set up the magnetic department at the Carnegie Institution of Washington. The principal task of this institution is to carry out

magnetic measurements over areas of the globe that have not yet been covered. This privately endowed institution has financed over 200 ground-based magnetic expeditions and has renewed magnetic surveys at sea, first in the Pacific Ocean on the wooden ship *Galileo* and then in other oceans on the world's first specially designed non-magnetic ship, the yacht *Carnegie*. This ship was in operation for 20 years until it perished in a fire in 1929.

During its glorious lifetime, the *Carnegie* covered about 300,000 sea miles and carried out magnetic measurements at several thousand sites, which made it possible to compile more reliable magnetic maps of the sea than ever before. After that, for nearly a quarter of a century no magnetic measurements were conducted at sea until 1956 when the Soviet non-magnetic schooner *Zarya* took part in the International Geophysical Year.

One of the characteristic peculiarities of magnetic data and magnetic maps is that they are constantly undergoing change and in time become out of date and unreliable. This is due to the fact that aside from short-term rapid variations of the earth's magnetic field caused by solar disturbances, after which the field reverts to its earlier state, there are also longer-term changes which are termed secular because of their duration. They gradually accumulate and utterly change the pattern of the field.

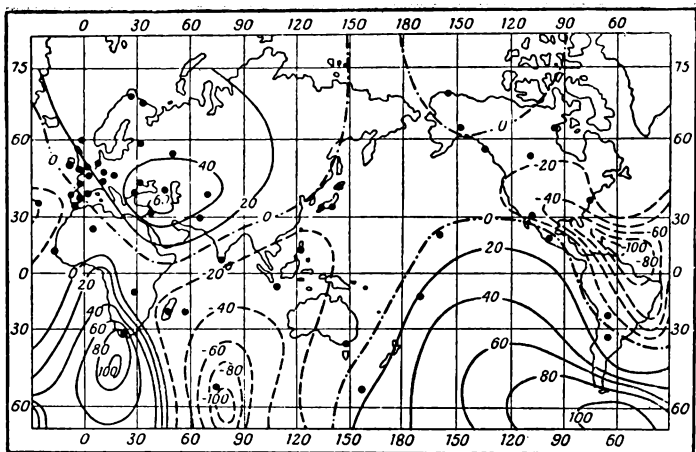
An illustration of the substantial changes that may occur is given by measurements of magnetic declination in London. At the end of the sixteenth century, the northern tip of the compass

needle was deflected eastwards from the geographic meridian by approximately 10° . Later it gradually began to move westwards, crossed the geographic meridian, and towards the end of the 18th century was deflected 24° from it. During the past two centuries the magnetic needle has been moving in the reverse direction, and now its northern tip departs westwards from the geographic meridian by only 10° . You can imagine what the situation for navigators would be like at sea or in the air if, despite the changes, old magnetic maps were consulted.

It is not yet known what causes the secular changes of the magnetic field. But it is known for sure that they are generated by processes occurring within the earth. All this goes to show that the inside of our planet is still very much alive.

There are vast areas on the earth where the magnetic declination and other magnetic elements are on the increase. In other regions, they are on the decrease; the position of these areas and their rate of change vary with time. To keep track of the secular changes and to obtain information necessary for introducing corrections into magnetic maps, magnetic surveys have to be conducted every five to ten years. True, a coarser grid of points may be used than in the original survey.

Since World War Two a veritable revolution has occurred in the technology of geomagnetic surveying. We now have self-orienting magnetometers that automatically align themselves with the force lines of the magnetic field and continuously measure the total field intensity in motion. These magnetometers were first used in making aeromagnetic surveys and, later, marine



Secular variations of the vertical component of the earth's magnetic field between 1950 and 1955. Solid lines indicate regions that showed an increase in the vertical component; dashed lines indicate a decrease. Number labels indicate magnitude of annual variation in gammas (one gamma equals one-hundred-thousandth of an oersted)

surveys. In order to eliminate the effects of the ship's iron on magnetometer readings, the instruments are placed in special non-magnetic gondolas suspended on non-magnetic cable from an aircraft or towed in a vessel at a considerable distance.

Scientists of the United States, Canada and Japan have adapted aircraft to measuring not only the total field intensity but also magnetic elements, including the magnetic declination. These measurements are carried out at altitudes

of several kilometres where the air is not bumpy; unfortunately, however, there is no guarantee that weak anomalies that might be recorded at sea level will not be by-passed.

The possibility of measuring the earth's magnetic field in motion has now made realistic the dream of making a magnetic survey of the entire globe. Only the co-operation of scientists from many countries will make this tremendous undertaking feasible, for the scale of work is enormous, and the survey and processing the materials obtained would have to be handled by unified methods.

At first a proposal was made to carry out a world-wide magnetic survey during the International Geophysical Year, but this was dropped for two reasons: first, magnetologists were very busy during the IGY with observations of other magnetic phenomena associated with solar effects; second, and this is no less important, the IGY was a period of the stormy sun and the disturbed state of the magnetic field. Surveys are better conducted when the sun and the earth's magnetic field are calm.

For this reason, the commencement of the world-wide magnetic survey was set for the International Quiet Sun Year. A participant in this work was the world's only non-magnetic schooner, the *Zarya*. During earlier voyages, when it crossed the Atlantic, Indian and Pacific oceans time and again continuously measuring the magnetic field at different latitudes, many fresh facts were elicited. It was found that the magnetic field at sea, even at great depths, is not so calm as had appeared after measurements by the *Car-*

negie, which were carried out only at selected spots spaced about a hundred miles apart.

It became clear that in addition to regions with a quiescent field, there are others where the ocean literally bristles with anomalies. True, they are not so intensive as on land since the sources of the anomalies frequently lie at depths of several kilometres.

During the IQSY, the *Zarya* repeated measurements in the Atlantic Ocean to find out what secular changes had occurred in this navigationally important region during the preceding years. Constant magnetic measurements also yield valuable material in studies of the little-known geological structure of the ocean bottom, which, as we know, accounts for over two-thirds of the surface of the globe.

Measurements by the *Zarya* introduced essential alterations in the magnetic maps of the oceans. Those who use these new and improved magnetic maps should recall with kind words the members of the *Zarya* expeditions. In the interests of science, they spent at times over a year on a stretch working under difficult conditions in a small wooden ship that hardly even reached out of the water. In the middle of this twentieth century, they plied the seas, all sails set, and pitted their three-hundred-horsepower engine against storms and hurricanes. The small reserves of fresh water, the pitch and toss of the vessel in an unaccustomed tropical climate with its heat and humidity could not prevent the crew and research staff from carrying out their important assignment: to gain knowledge about the earth.

During stop-overs at foreign ports with mag-

netic observatories in the vicinity, the scientific workers of the *Zarya* checked their instruments against those of the observatories and thus ensured comparability of magnetic measurements made in various parts of the globe.

A big contribution to the world-wide magnetic survey has been made by American scientists who continue to conduct measurements of magnetic declination and other magnetic elements in aircraft. In the "Magnet" Project, the airplanes doing the magnetic measurements fly routes spaced 200 to 300 miles apart. Measurements have been made over the United States, a substantial portion of the Atlantic and Pacific oceans, and also the Arctic and the Antarctic, bringing the total route to over 200,000 miles.

Canadian scientists undertook similar measurements over the vast land areas of their country and over the northern part of the Atlantic Ocean. Japanese investigators surveyed the islands of Japan and the adjacent seas during the IQSY.

In a number of other countries, magnetic surveys of the respective territories are being repeated so as to obtain fresh data on the secular variations of the field. Many oceanographic vessels are engaged in measuring the total intensity of the magnetic field in the stormy waters of dozens of seas and oceans. Magnetic measurements are also conducted on all tractor-train treks deep within the Antarctic continent and on drifting stations in the Arctic.

With the advent of spacecraft it is now possible to make magnetic surveys and measurements not only on the earth's surface and at low altitudes, but quite some distance out in space. The

Columbus of magnetic space was the third Soviet satellite, Sputnik 3, launched in 1958. This was followed by the American Vanguard satellite. These space vehicles were very successful in making measurements of the magnetic field. They demonstrated that magnetic surveys via satellites make for a more precise analysis of the earth's magnetic field than is possible by ground-based data alone.

On the basis of an agreement between the governments of the U.S.S.R. and the U.S.A., Soviet and American scientists carried out a satellite-directed magnetic survey of the earth during the IQSY.

Magnetic surveys of circumterrestrial space have certain advantages over other types of surveys. To make magnetic surveys over a total route of 200,000 miles, aircraft were in operation for several years. A satellite can cover the same distance in less than a day. What is more, there are no inaccessible places. Orbiting at a variety of altitudes, satellite vehicles report on how anomalies decay with altitude, and this helps to pinpoint the location of their sources relative to the earth's surface.

Repeated magnetic surveying from satellites will help solve a most interesting problem: the variation of the magnetic moment of the earth with respect to time. Very important facts about the structure and behaviour of the magnetic field at large distances from the earth have been obtained by the Soviet Electron satellites and the American Explorer series that were launched in accordance with the IQSY programme. Their highly eccentric orbits allow them to make pe-

riodic cuts through the magnetosphere and report on events inside it, on the boundary lines and beyond, out in the interplanetary magnetic field.

The whole world-wide magnetic survey will take a good number of years yet, despite the sophisticated space and ground technology. However, a very substantial foundation of this great undertaking has already been laid in the International Quiet Sun Year.

Earth currents

These currents were first detected, as is often the case, because of trouble. Last century saw the first long-distance telegraph lines put into service. And the earth served as their return line. It was soon found that communications were at times suddenly disrupted. Telegraph apparatus would spontaneously tap out gibberish, and the tension in the lines grew to prohibitive magnitudes. The time of such disruptions coincided with the onset of intense magnetic storms and auroral displays.

Further investigations brought to light the fact that there are always stray electric currents wandering about inside the earth; they are usually rather feeble and change both in magnitude and in direction. When they get into telegraph lines earthed at both ends they disrupt communications. Earth currents were put under surveillance, which was not difficult because no complicated equipment was needed. In fact, it suffices to put iron rods into the earth a few hundred metres

apart and connect them with cable lines. The current intensity in the lines may be measured with a galvanometer.

Ordinarily, when the magnetic field is quiescent, the earth currents are weak and the difference of electric potential between two points on the surface does not exceed several millivolts per kilometre. But when the magnetic field of the earth comes under the action of solar corpuscular streams it gets excited and induces much heavier earth currents with potential differences of the order of hundreds and even thousands of millivolts per kilometre.

An earth-current storm of this magnitude is no simple affair. For instance, on April 16, 1938, earth currents disrupted communications on long-distance telegraph lines almost over the entire Soviet Union. One can easily imagine the potential disasters this is capable of. Quite understandably, after this occurrence, the Soviet Union set up a permanent information service on the state of the magnetic field; it later grew into a forecasting service of magnetic disturbances.

Despite the simplicity of earth-current research and the obvious necessity of such studies, little headway was made for a long time in this sphere. Strangely, the stumbling block was in the form of trams, electrified railways, and the underground railways operating on direct current with the rails as the return line. The large stray currents generated by them interfere with the registration of the comparatively weak earth currents. Also, interest in earth currents somehow declined when it was found that their behaviour depends on the geology and orography of the vi-

cinity, for this complicates deciphering planet-wide peculiarities in current variations.

Investigations were greatly expanded during the International Geophysical Year. Sixty stations set up at numerous magnetic observatories in tens of countries of the world, including the particularly interesting regions of the Arctic and Antarctic, carried out continual observations of this phenomenon.

During the IQSY, new stations and a major portion of the earth-current stations set up during the IGY continued the observational work. Particularly gratifying was that the number of such stations increased on the American continent. One was established in Cuba. Soviet researchers opened up 18 stations covering an immense area between Alma-Ata, Murmansk, Petropavlovsk and Alushta (in the Crimea).

The Antarctic was also attacked scientifically. The Soviet ship carrying members of the first Soviet Antarctic expedition in 1956 set out with everything imaginable on board, but the biggest surprise to anyone inspecting matters would have been the earth loaded in the hold. Just soil on a trip to the ice continent so that electrodes could be inserted in order to study earth currents. Later, however, scientists learned how to do the trick without imported earth.

It was found that in polar regions disturbances and real storms are especially frequent and intense. Of course, during large magnetic storms, heavy earth currents "flow" even in medium latitudes, but their real domain is the far north and the far south, which are the customary areas of the auroras.

Earth currents come with changes in the magnetic field. Quite natural, therefore, that there should be much in common between them: the frequency of both depends on the cycle of solar activity and both have a tendency to recur every 27 days. Whence their kinship with the aurora, variations in the ionosphere, and even with disruptions of long-distance communications. When in 1961 and 1962 American scientists correlated earth-current pulsations with frequent and small beats and brightness changes of auroras over Alaska, a remarkable coincidence was found in the timing of these phenomena, in their onset and in the pulsation periods.

Unlike ordinary magnetic records, the registration of earth currents is conducted with great rapidity; this makes it possible to record oscillations with a period of only a few seconds and catch even very slight and extremely rapid changes in the magnetic mood of the earth. What is more, earth currents, these "moles digging in the earth", have been found capable of recording certain processes that occur at high altitudes.

For example, when, prior to the Moscow agreement on the prohibition of atomic explosions in the atmosphere, the Americans exploded three nuclear devices at 500-km altitude over the Southern Atlantic, scientists of many countries were able to determine the times with great accuracy on the basis of earth-current records. The point is that despite the low yield of these devices, they caused disturbances in the magnetic field that were accompanied by characteristic rapid pulsations of earth currents, and these were caught by instruments in a round-the-clock service.

Just before the beginning of the International Quiet Sun Year, a variety of magnetic field and earth-current pulsations was detected and given the poetical name of pearls. These are micropulsations with a period of from 0.3 to 2.5 seconds; they are detected on the basis of characteristic deviations that are superimposed on ("threaded onto") the ordinary record.

The pearls frequently recur on the trace of the record at equal time intervals, usually every few minutes. It is believed that these embellishments are the sun's gift to the earth; they are apparently associated with the movement of blobs of solar plasma along the force lines of the magnetic field and with their drift round the earth. Another surmise is that these pulsations are caused by hydromagnetic waves of a special kind that arise on the boundary of the earth's magnetic field under the action of the solar wind.

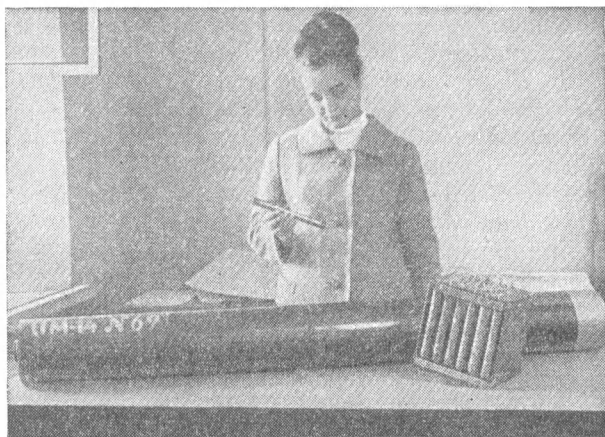
Which of these hypotheses is closer to the truth will be evident after an analysis of the IQSY studies, in particular observations at conjugate magnetic points in high latitudes. Information about earth currents will be utilized not only in studying sun-earth relations, but also in probing the inner structure of the earth.

Today, on the initiative of Soviet scientists, workers in tens of countries are co-ordinating efforts for joint investigations into the "Upper Mantle of the Earth", the aim being to extract information about the structure of this planet of ours, about the inner regions of the globe, of which, to our shame, we know so little. Earth currents should be a great help in this work. A good deal of information concerning the internal struc-

ture of the earth, its physical properties and above all the electrical conductivity of the rocks down to depths of hundreds of kilometres may be obtained in joint studies of magnetic and earth-current variations.

Heralds from distant worlds

Visitors from far-off worlds have been the theme-song of science-fiction writers for ever so long. In actuality such visitors exist, but not intelligent beings, simply charged particles that stream into the earth from deep space at every angle. Incidentally, we might begin not with the universe—the infinitely large macroworld—but



New GM-14 counter for cosmic-ray telescope (designed at IZMIRAN). Compare this with a section of an air-borne station (PJK-4) for registering cosmic rays

with the almost infinitely small microworld of elementary particles.

The French physicist Antoine Henri Becquerel, working in his modest laboratory, discovered a new phenomenon in 1896. He found that uranium salts emit a radiation capable of ionizing the air and, like X-rays, of acting on a photographic plate wrapped in black paper.

Studies of the new radiation led Pierre and Marie Curie to the discovery of radioactivity. It was soon established that the rays emitted by radioactive elements, including uranium salts, are of three varieties: alpha rays, which are the nuclei of helium atoms carrying two positive charges, beta rays, which are like the cathode rays and are actually electrons, and gamma rays, which are akin to X-rays and are an electromagnetic radiation.

As is often the case, the new phenomenon was checked through all the elements and it soon transpired that they could be divided into two classes: radioactive and non-radioactive. Here it came to light that the ionizing radiation is truly ubiquitous. No matter where physicists hid their ionization chambers, in the deepest pits or at great altitudes above the earth, the air inside their chambers was always ionized.

In 1911, the Austrian physicist Victor Hess sent his instruments aloft in balloons ten times to 5-km altitudes. He found that up to about 1 kilometre, ionization in a closed vessel gradually diminished and then began rapidly to increase. And at 5 km, ionization was already three times that at the earth's surface. His conclusion was that there must exist a highly penetrating radiation of

extra-terrestrial origin that pierces the atmospheric thickness and, together with radioactive substances, may be responsible for a part of the ionization in closed vessels on the earth.

The conclusions of Hess were corroborated by measurements made by another German worker, W. Kohlhörster, who demonstrated that at an altitude of 9 km ionization becomes ten times that at sea level. Even so there were many prominent scientists who for a number of years doubted the extra-terrestrial nature of sources of penetrating radiation.

It was quite natural to expect that the newly discovered radiation, which came to be known as cosmic rays (or cosmic radiation), might tell us a great deal about the natural conditions existing in the distant areas of the universe where it originated and about properties of matter in general. Whence the obvious interest in this new physical phenomenon.

At first physicists focussed attention on disclosing the role of cosmic radiation in atmospheric ionization and on determining its ability to penetrate various materials.

In 1931 and 1932, the noted Swiss physicist and pioneer of stratospheric flights, Auguste Piccard, reached a height of 16 kilometres. The Soviet pilots, G. A. Prokofyev, E. K. Birnbaum, and K. D. Godunov, in 1933 flew to 19 km above sea level in the stratospheric balloon (stratostat) SSSR-1. In 1934, three intrepid Soviet pilots, P. F. Fedoseyenko, I. D. Usyskin and A. B. Vashenko, reached a record 22 kilometres but perished in the attempt. A year later K. Ya. Zille, Yu. G. Prilutsky and A. B. Verigo of the Soviet

Union successfully reached the 16-km level. The physicist Verigo, to slow down the dangerous descent, left the gondola in a delayed parachute jump from this extreme altitude. That same year physicist Carl Anderson and pilot Stevenson of the United States, reached 22,066 metres in the balloon Explorer II.

All these efforts and sacrifices were not sporting achievements. Piccard, Usyskin, Verigo, Anderson, and Prokofyev were not out to chalk up records. They were after cosmic rays and studied the variation of conductivity of the air and the radiation intensity as a function of altitude.

At the same time, investigations continued into the ability of radiation to penetrate through various media. Radiation was measured in ionization chambers protected by lead shielding of various thickness, in deep mine shafts, in clefts in glaciers, in mountain lakes at various altitudes, and aboard submarines. Physicists found that it could be detected with sensitive instruments even under layers of water three kilometres in thickness, though it was weakened by a factor of 100,000,000!

Studying the absorption of radiation by lead, researchers found that it could be divided into two components: soft (absorbed in a layer of lead of thickness 8 to 10 cm) and hard (capable of penetrating thicker shielding without perceptible absorption). This at first glance purely formal division had a profound physical meaning. Subsequently, it was learned that the different penetrating ability is connected with the composition of the particles that make up the radiation.

At this time, ionization chambers were being

supplemented with ionization counters in the study of radiation. Unlike the chambers that record only the total ionization, counters note the ionization generated in the passage of every single charged particle. In 1934, the Soviet physicist S. N. Vernov designed a special probe for studying cosmic rays that transmitted by radio the readings of counters carried aloft in balloons.

In 1911, the English physicist Charles Wilson devised a novel method for obtaining photographs of ionized tracks that are produced in gases traversed by charged particles. The Soviet physicist D. V. Skobeltsyn perfected this method by placing the Wilson cloud chamber, as it was called, into a magnetic field. It was then possible, when observing particle trajectories curved in the magnetic field, to determine whether they were charged positively or negatively and to gauge their velocities and energies.

For a number of years Skobeltsyn studied the gamma rays emitted by radioactive substances and their interactions with gas molecules with the aid of his improved cloud chamber and noted strange tracks that never curved in a magnetic field. Calculations demonstrated that the energy of particles that could leave such tracks would have to be many times that of particles generated by radioactive substances. And Skobeltsyn presumed these particles to belong to the cosmic rays.

This discovery laid the foundation for the study of the nature of cosmic rays. Fresh findings came one right after the other. In 1932, the American physicist and experimenter Carl Anderson—the same one who went aloft in a stratostat to 22 kilometres to catch cosmic rays—used a cloud

chamber and detected a hitherto unknown particle, the positron, in these cosmic rays. This is the antiparticle of the electron: everything is the same, only the charge is positive. Then six years later, working together with S. H. Neddermeyer, he found the mu-meson in cosmic radiation. This particle can have a positive or negative charge equal in magnitude to that of the electron, but has a mass intermediate between the electron and proton mass. The name meson comes from a Greek word meaning "intermediate".

Subsequent studies of tracks left by cosmic rays in the Wilson cloud chamber and in nuclear emulsions showed that mu-mesons also have kin with greater mass. Some, like the pi- and K-mesons, could also be neutral.

Characteristic of mesons is that, in contrast to electrons, protons and positrons, they are unstable and have very short lifetimes: of the order of a millionth of a second for mu-mesons, and about one-hundred-millionth of a second for the pi- and K-mesons.

After a brief life they decay into other particles. K-mesons convert into positrons, pi- and mu-mesons; charged pi-mesons turn into mu-mesons, while neutral pi-mesons generate high-energy photons. Photons are quanta of light, of X-rays, and of gamma radiation. When they collide with the nuclei of atoms, they turn into electron and positron pairs.

To date, scientists have discovered about 15 elementary particles in cosmic radiation. In addition to photons, electrons, positrons, and a variety of mesons, cosmic radiation also contains protons and neutrons. In smaller quantities than

protons (hydrogen nuclei) we find the nuclei of the heavier elements: helium, lithium, and others right up to iron and even beyond. The relative quantities of these nuclei correspond to the abundance of the elements in nature at large. It is assumed that cosmic radiation should also have neutrinos; a neutrino is a particle with a zero charge and a very small, possibly zero, rest mass. It has a fantastic penetrating capacity enabling it to pass through the entire earth with the greatest of ease.

The particles of cosmic radiation possess varying degrees of penetrability. After the neutrino, whose existence in cosmic rays has yet to be demonstrated, the hardest (most penetrating) particles are the mu-mesons. The electrons, positrons, photons form the soft component of cosmic radiation. The hardness of particles is determined not only by their energy, but also by their losses in interactions with substances. The mu-meson is most economical in giving up energy; it is mostly spent on ionization.

Measurements of the total intensity of cosmic radiation obtained by balloons and rockets show that up to 20 km there is a rather rapid increase, but from there on to 50 km it diminishes and afterwards remains practically constant. At about 20 km the intensity is twice that at the outskirts of the stratosphere and fifty times that at sea level.

This peculiar variation of cosmic-ray intensity with altitude may be accounted for only by the simultaneous action of two processes: on the one hand, the multiplication of the primary radiation in the atmosphere with the generation of second-

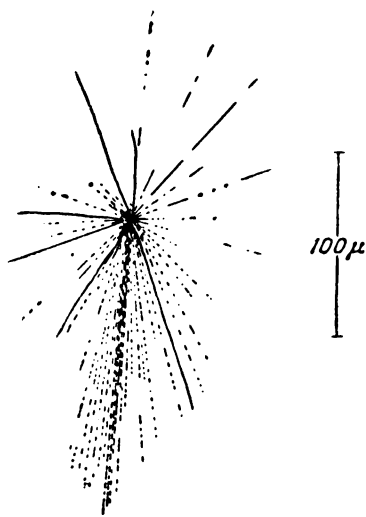
ary rays as a result, and, on the other hand, the absorption of the primary and secondary rays as they penetrate deep into the atmosphere.

The primary cosmic rays consist mainly of atomic nuclei of different elements. About 83 per cent is made up of protons, which are hydrogen nuclei, about 16 per cent are alpha particles, or the nuclei of helium, and only about 1 per cent consists of the nuclei of other (heavier) elements. Comparatively recently, high-energy electrons in small numbers were detected in cosmic radiation.

Few primary particles visit our planet: only about one or two particles per second per square centimetre of surface on the average. Therefore the total energy of cosmic radiation is small, despite the stupendous energies of individual particles: it does not even exceed the energy of the stellar light falling on the earth. But in energy and velocity, the primary particles are almost unsurpassed: they hurtle earthwards with velocities close to that of light, which as we recall, is the absolute of nature's speed records.

Particle energies are measured in electron volts (eV) and cosmic-ray particles have energies up to 10^{18} (one followed by eighteen zeros)! At least one particle has been observed to have the fantastic energy of 10^{19} eV. Even a single proton with that energy could, if properly harnessed, keep a one-watt lamp burning during one whole second.

No laboratories anywhere in the world, even those that have produced whole families of elementary particles, are capable of speeding particles to anywhere near such energies as nature offers us in cosmic radiation. The highest man-produced



Multiplication of particles in a nuclear collision. The photographic plate was sent to 30-km altitude. This star consists of at least 95 particles

particle accelerations today are measured in a few thousand million electron volts, which is 10^9 eV or so; now this is nine or ten orders of magnitude less than the energy of those primary particles that we have been discussing.

Where do these super-high-energy particles come from? So far we do not have a final answer. True, it has been established that beyond the limits of the earth's magnetic field these particles come in uniformly from all directions, unlike, say, the light of stars, which is greatest in the direction of the Milky Way. But this does not

mean very much since we do not yet know the sources that send us their fleet-footed messengers.

It has been suggested that cosmic rays are ejected in the outbursts of supernovae which astronomers have occasionally observed in our Galaxy. But, first of all, this is only a conjecture, secondly, the processes that occur in such flare-ups are not yet fully known. As we have already said, during recent years it has been found that certain (true, very rare) solar flares are attended by outbursts of cosmic radiation, the maximum energy of which is about 10^8 eV; that is, significantly lower than the energy of galactic cosmic rays.

To get some idea of how cosmic rays are accelerated to their high velocities and stupendous energies, recall the circus trainer as he cracks his whip over a horse circuiting the arena and gaining speed with every turn. One of the hypotheses is that the universe exhibits something similar: particles generated by some distant star get caught up in magnetic fields scattered about in space and for millions of years undergo acceleration in the course of their wanderings, acquiring the truly fantastic energies that we witness.

The genesis of secondary particles of cosmic radiation may be clearly seen in a Wilson cloud chamber and in photographs of tracks left in the wake of particles passing through nuclear emulsions. High-energy particles of the primary cosmic rays collide with atomic nuclei in the air and knock out protons and neutrons. Both gain energy at the expense of the primary particles and in turn can collide with other nuclei, thus producing a new generation of protons and neutrons.

This process of the formation of secondary (tertiary, etc.) particles continues until the energy of the primary particles and the newly formed particles is dissipated to the extent that they can no longer destroy. In such a nuclear-cascade process, a single particle can give rise to a whole shower of secondaries.

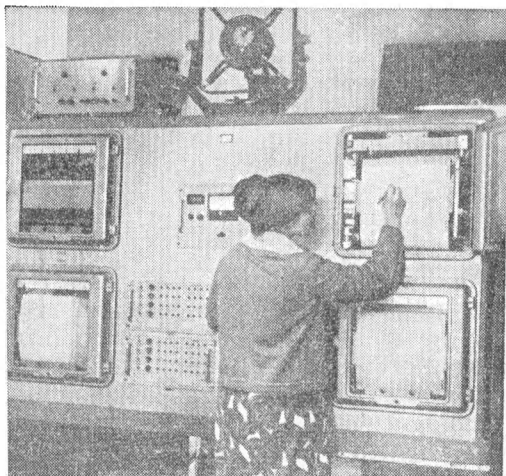
To continue, when primaries collide with atomic nuclei, they may also generate charged and uncharged mesons, including pi-mesons. Charged mesons decay into mu-mesons, and neutral mesons disintegrate into photons, which collide with atomic nuclei to produce electron-positron pairs. The result is an electron-nuclear shower. It has been established that the so-called extended air showers generated by individual high-energy primary particles sometimes consist of millions of secondary particles and cover tens of thousands and even millions of square metres of the earth's surface.

Scientists have calculated that at the earth's surface there is only one particle for every 100,000 secondaries that has come to us from deep space. Approximately two-thirds of the secondary particles at sea level are mu-mesons. The soft component is made up mainly of electrons, positrons and photons. There is a small quantity of neutrons, whose contribution to the total cosmic-ray intensity comes out to about one per cent. Cosmic rays ionize the air at sea level producing about two ion pairs in every cubic centimetre per second.

The intensity of both components of cosmic radiation increases with altitude, that of the soft component increasing faster than the hard com-

ponent. At about 15 km the intensity of the soft component exceeds that of the hard component by roughly three times; from there on upwards it begins to fall off rather rapidly and at the fringe of the stratosphere it is practically zero.

To elucidate the nature of the primary cosmic rays, for one thing in order to find out whether they consist of charged particles or photons, as was supposed at one time by some physicists, it is important to establish whether there is any geomagnetic effect in the distribution of their intensity due to the earth's magnetic field. It would be natural to expect a more or less definite result from measurements of cosmic-ray intensity in the



Visual records of IZMIRAN cosmic-ray station

stratosphere where there should be more primary particles.

The physicist G. Clay, of the Netherlands, took his instruments to the island of Java. In the course of the voyage he found that the intensity of cosmic radiation at the equator is considerably less than near Amsterdam, which is located in medium latitudes. Which means there is a latitude effect in the distribution of cosmic rays.

During this expedition, Clay attempted to measure the latitude effect in cosmic-ray intensity in the stratosphere as well, but his results here were later found to be in error. More reliable data were obtained by a group of American investigators under the leadership of Robert A. Millikan and Soviet physicists headed by S. N. Vernov.

It was found that the intensity of cosmic radiation in the stratosphere increases, as one moves from the equator to higher geomagnetic latitudes, by a factor of three. But again the increase continues only to 50° . Numerous measurements by balloons in higher latitudes, right up to the geomagnetic pole, did not reveal any further increase in cosmic-ray intensity.

The American investigator H. V. Neher and his collaborators using ionization chambers and special counters observed cosmic rays during a flight from North America to South America and back again at an altitude of about 10 km. The result was that more particles arrive from the west than from the east. This asymmetry of cosmic radiation is more pronounced near the geomagnetic equator and is absent at 50° latitude.

Though scientists have been after the secret of

the distribution of cosmic-ray intensity for about 30 years, the full picture is still rather obscure. During recent years attention has been focussed on properly placing the equator of cosmic radiation.

When it was found that geomagnetic phenomena affect the primary cosmic rays, this finally confirmed their extra-terrestrial origin and demonstrated that they consist of charged (mostly positively) particles.

As we have already had occasion to relate, the theory of motion of individual charged particles in the earth's magnetic field was elaborated by Carl Störmer to account for auroras and magnetic storms. True, magnetic storms do not always fit the theory, but then it is a question not of individual particles but of whole dense streams of particles. But the theory is very suitable when it comes to explaining how geomagnetism affects cosmic radiation where the particles are separate, each one on its own.

On Störmer's theory it is assumed that all particles emanate from a single source, the sun, and that in the cosmic rays they move earthwards from all directions with the same probability. If there is no magnetic field, that is as it should be. But then the particles enter the sphere of action of a magnet (our earth) and the latter begins to sort out the particles depending on the energy and direction from which they enter its field.

Depending on the magnetic latitude, every region of the earth's surface has its own critical, limiting energy for the entry of charged particles. Particles with energy less than critical for the given place and direction of motion are not able

to enter. Those with greater energy come in without any trouble.

The lower the geomagnetic latitude of a place, the greater the energy must be for a particle to enter. A primary wanting to reach the magnetic equator vertically must have an energy of at least 14,900 million eV. At geomagnetic latitude $\pm 30^\circ$ it would need only about 10,000 million eV. Hence, particles which cannot make the magnetic equator are still able to enter the higher magnetic latitudes. Thus, the intensity of radiation increases with magnetic latitude.

For particles moving vertically, the critical energy depends on whether they are positively or negatively charged. The picture is quite different when particles are in motion from west to east. For a positive particle to reach the magnetic equator from the west at an angle of 45° to the vertical it must have an energy of at least 10,000 million eV. Coming in at the same angle from the east, its minimal energy must be two and a half times greater. For negative particles the relationship is reversed: they find it easier to reach the earth from the east than from the west. The intensity of cosmic rays arriving from the west is greater than of those coming from the east. This indicates a predominance of positive particles in the cosmic rays.

Let us note yet another circumstance. As we have seen, the latitude effect in cosmic rays is cut off at the geomagnetic latitude of $\pm 50^\circ$, no further change occurs in the intensity. Which means that there are no particles in cosmic radiation with energy less than one thousand million electron volts. If there were, the cut-off in the lati-

tude effect would occur at higher latitudes or would not occur at all.

However, as studies have shown, the spectrum of primary cosmic rays is cut off on the low-energy side differently depending on the solar activity. During years of minimum solar activity, the cosmic rays become softer, so to say. It would therefore be expected that the cut-off in the latitude effect of cosmic rays should shift to higher magnetic latitudes during this time.

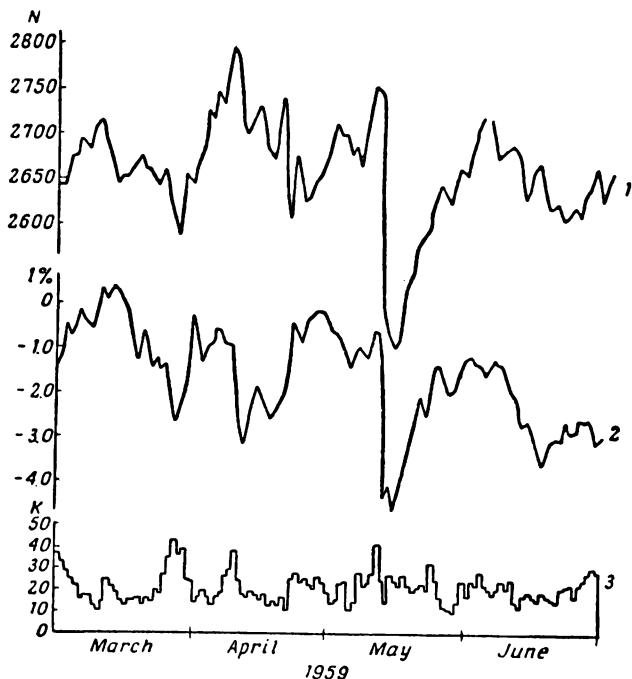
At one time it was thought that cosmic-ray intensity is distributed over the globe under the action of the earth's field of homogeneous magnetization. Accordingly, it was supposed that the equator of cosmic radiation coincides with the geomagnetic equator. However, determinations of the location of the cosmic-ray equator carried out during the IGY on ships and aircraft showed that it is in better coincidence with the equator of magnetic inclination. Whence we may conclude that the distribution of cosmic-ray intensity is affected not only by the field of homogeneous magnetization but also by the field of world magnetic anomalies. The theory helped to establish the height of the magnetic threshold at all "doors" through which our cosmic guests enter.

Does that mean that every particle and its numerous progeny have only one permanently established site of impact depending on the energy of the particle? During the International Geophysical Year, when the whole world was studded from pole to pole with ground stations measuring particles of a wide range of energies, it was established that there is no such absolute predetermined destiny for a given particle.

It turned out that particles lucky enough to approach the globe during an intense magnetic storm may sometimes reach the earth's surface in places that are ordinarily prohibited to them. For example, particles with low energies are occasionally able to penetrate to lower latitudes than is prescribed. This is added proof that the structure of the magnetic field and the behaviour of the force lines which serve as entry routes for charged visitors from deep space undergo violent changes during a storm.

The intensity of cosmic radiation at the earth's surface does not remain constant either. The greatest changes are due to the whims of the atmosphere, particularly the layers that are mainly responsible for the generation of secondary particles. A change in atmospheric pressure of only one millibar gives rise to a change in cosmic-ray intensity of 0.14 per cent. Now atmospheric pressure is changing all the time. During the passage of a meteorological front, it can jump several tens of millibars at once. This barometric effect in cosmic rays was first noted as far back as 1928 by the Soviet physicists L. Mysovsky and L. Tuvim.

An increase in temperature in the stratosphere brings with it an expansion of the layer that produces mu-mesons. This accordingly increases the distance they have to cover to the earth and, hence, the probability of their decay prior to reaching the surface. As a result, the hard component of cosmic radiation, which consists mainly of mu-mesons, exhibits a negative temperature coefficient. On the contrary, neutrons, whose lifetime is measured in minutes, have a barometric coeffi-



Forbush effect observed in 1959

1—mean diurnal values of neutron component of cosmic rays based on observations in Irkutsk; 2—mean diurnal values of meson component based on ionization-chamber observations in Moscow; 3—variations of magnetic activity (evaluated on a ten-point scale)

cient, but there is practically no temperature coefficient.

When judging changes in the primary radiation on the basis of measurements at the earth's surface, one has to introduce meteorological corrections into these ground-based measurements. This means knowing the "coupling coefficient" between changes of the primary radiation and changes in the atmosphere at the earth's surface; one has to know how the cosmic-ray spectrum at one altitude differs from that at another for different latitudes.

In the latter part of the 1930s, a continuous registration of cosmic-ray intensity was initiated. For this purpose, counter telescopes and a special kind of ionization chamber designed by Compton were used. These greatly enhanced the accuracy of measurements. Counter telescopes permitted measuring simultaneously and separately the total intensity and the intensity of the hard component. Widely used during the IGY were neutron monitors designed by the American physicist G. H. Simpson, which permitted following variations of the low-energy (less than 15 GeV *) portion of primary cosmic radiation.

That cosmic-ray intensity could vary during magnetic storms was noted in 1937. Then a year later, the organizer of a network of cosmic-ray stations set up by the Carnegie Institution, Scott Forbush, reported a remarkable phenomenon. It appeared that during the magnetic storm of January 16, 1938, cosmic-ray intensity diminished a whole 6 per cent, and there was a definite cor-

* One GeV equals 1,000 million electron volts.

relation between the variations of cosmic-ray intensity and the variations of the horizontal component. This became known as the Forbush effect, after the discoverer.

The decrease in cosmic-ray intensity caused by the Forbush effect is sometimes sudden and sometimes gradual. Return to normal intensity, as in the case of magnetic storms, may take several days. The Forbush effect is particularly marked in the neutron component. It is most often observed during magnetic storms that follow immediately after solar flares attended by special bursts of radio emission.

But the strange point is that intense magnetic storms are encountered that do not reveal any Forbush effect at all, which complicates the phenomenon still more.

The first conjecture was that the relationship here is not direct but roundabout: events on the sun act on the earth's magnetic field and generate a circular current, the magnetic field of which deflects cosmic rays away from the earth. But this was refuted by Simpson, who found that the actually observed changes in intensity are such as to be unaccountable by such variations in the vicinity of the earth. What is more, a satellite (Explorer 6) detected the Forbush effect far beyond the limits of the magnetosphere of the earth.

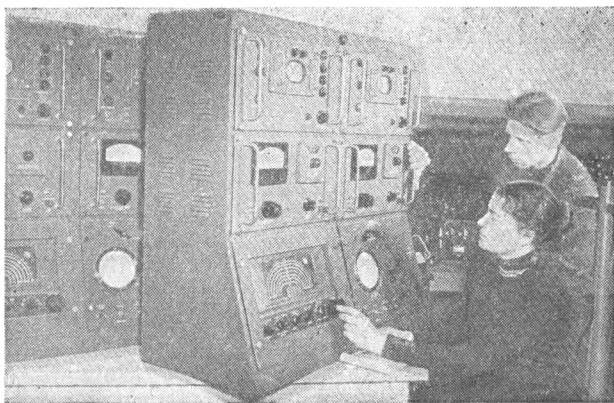
Obviously the matter is quite different; rather it is a reflection of changes in cosmic-ray intensity that affect the whole solar system. Apparently, the sun's radiation is somehow able to hamper the influx of cosmic radiation throughout the whole solar domain and not only in the vicinity of our planet.

But how does this occur? So far there is no reliable answer. All we have is hypotheses based on a conjecture advanced by the prominent Swedish scientist Hannes Alfvén, according to which the solar plasma ejected in a solar flare may carry with it a magnetic field. Whether this field is the magnetic field proper of "whiffs" of plasma or patches of magnetic lines of force "captured" from the sun or from the interplanetary magnetic field is not clear. It is believed that the magnetic field of such streams or clouds of conducting plasma can sweep up and carry off galactic cosmic rays from some limited region of interplanetary space and thus, temporarily, reduce their intensity.

But then how is one to account for the 11-year periodicity in cosmic-ray intensity? During years of maximum solar activity their intensity is known to be one-half that during minimum. Besides, during minimum years less energetic particles appear that are not observed at all during maximum.

It is presumed that at maximum solar activity, the clouds of solar plasma ejected by the sun with their magnetic fields fill the interplanetary space more densely. Cosmic rays coming from deep space in the Galaxy have to overcome a magnetic barrier put up by the sun before they can enter the interplanetary space of the solar system. A certain portion of the particles are scattered in the process, and the less energetic ones are simply reflected back.

During minimum solar activity the density of such clouds drops and the intensity of galactic particles that break through into our interplane-



Apparatus being checked at the Institute of Space Physics Research and Aeronomy (Yakutian Branch of the U.S.S.R. Academy of Sciences)

tary space and the earth increases; less energetic particles put in an appearance.

A no less remarkable discovery was made at the beginning of 1942. On February 28, very unexpectedly all charged-particle counters at most stations frantically speeded up the count. Ionization chambers noted an increase in intensity, at places by tens of per cent, at others even hundreds of per cent. This was the commencement of a burst of cosmic radiation. The phenomenon was subsequently reported a number of times, but still, it is quite out of the ordinary and does not occur every year by any means.

The intensity of the bursts increases with magnetic latitude and with altitude: in the strato-

sphere they are stronger than at sea level. The largest recorded burst occurred on February 23, 1956. It was even felt near the geomagnetic equator, where the cut-off threshold for particles arriving vertically is equal to 14.9 GeV. Cosmic-ray bursts affect the neutron component most markedly. During this burst, in Ottawa (Canada) the neutron component increased approximately thirty times.

All subsequent bursts were observed in medium and high latitudes. The 1956 burst, like most other phenomena of this kind, was observed after a solar flare. Ordinarily, there is an interval of from 30 minutes to 2 hours between a solar flare and the onset of a burst of cosmic rays, and they persist for several hours.

Cosmic-ray bursts indicate that cosmic radiation may originate not only in distant galaxies but also in our own sun.

Studies of the composition of solar cosmic radiation carried out during the IGY have shown that in the main it consists of protons and nuclei of helium. Cosmic rays have particles with a wide range of energy. From data obtained by the satellites Explorer 12 and Explorer 14, particles with higher energies arrive before lower-energy particles.

Bursts of solar cosmic rays consisting of particles with energies comparable with those of the soft cosmic rays of galactic origin are comparatively rare. But bursts of solar protons with energies of hundreds of electron volts and less are observed scores of times a year. Their energy is too low for them to reach the earth's surface even in high magnetic latitudes, but they may be

observed with satellites, rockets and balloons. These protons make their whereabouts known by enhanced absorption of radio waves and by a special type of night airglow, which we shall go into in more detail later on.

And now a few words are in order about two types of periodic variations of cosmic-ray intensity: seasonal and diurnal. These variations are very small: seasonal do not exceed 2 per cent, diurnal, 0.5 per cent. The maximum for seasonal variations comes in the winter of the appropriate hemisphere, for diurnal variations, in the afternoon, local time.

Many workers are racking their brains over the causes of these variations, but so far without success. Are they due to meteorological factors (density, temperature of atmosphere, height of atmospheric layers through which the particles break their trails) or are they the result of certain changes in the primary radiation itself? It is still not clear. And it is not so simple to figure this out because the behaviour of the secondary particles we deal with at the surface depends on too many factors, most of which are unknown.

It would be very interesting to find out whether there are cosmic-ray variations associated with time reckoned from the apparent motion of stars and not the sun. The sidereal day, often used by astronomers, is the unit of this time. The sidereal day is the exact time of rotation of the earth on its axis: 23 hours 56 minutes 4.1 seconds. True, the onset may be in the daytime or at night depending on the season. Yet this day is very convenient for solving problems associated with the apparent revolution of the firmament.

Now if it were possible to find a regular relationship between an increasing or decreasing flux of primary cosmic rays and sidereal time, this would mean that they have a preferential direction of arrival on the earth. This would help to determine the origin of the mysterious galactic wanderers.

Unfortunately, so far no one has been able to establish any such sidereal-diurnal variations of cosmic radiation. Ten years ago the observational facilities were still imperfect and the network of stations and observatories was too sparse. During the IGY a proper network was set up, but the sun was "on the warpath" and the excessive activity was too much for such delicate experiments. During the IQSY, when the sun had calmed down, attempts were made in many countries to trace sidereal-diurnal variations.

Cosmic-ray intensity patterns "like" to recur every 27 days. Studies by a number of workers have shown that this tendency is sometimes observed during certain periods, particularly during maximum solar activity, but it is not stable. The amplitude of 27-day variations during minimum solar activity is close to zero, while at maximum it lies between 0.1 per cent and 0.5 per cent.

"Hunters" of cosmic rays at over a hundred stations in thirty countries (including 15 American, 14 Soviet, 8 Argentine, 7 French, 7 Australian, and other stations) are now equipped with refined apparatus. Complicated neutron monitors, ionization chambers reminiscent of H. G. Wells' martian tripods, batteries of Geiger counters combined into whole telescopes—such were the facilities delivered during the IGY to the far

corners of the earth, from the Arctic to the South Pole.

What scientists are eagerly waiting for is a comparison of the materials obtained, for they can now add information gained with more sophisticated instrumentation: supertelescopes and supermonitors of recent design that speed up the count of charged particles and thus enable the law of large numbers to eliminate possible statistical errors.

IQSY workers went in search of cosmic particles everywhere: under the earth, on the surface, at sea and in the skies. There are also particle counters on the Soviet non-magnetic schooner *Zarya* and on the West German oceanographic vessel *Meteor*, and also on the American expedition ship *Eltanin*. Swedish scientists are measuring cosmic rays on the *Stratus*, a vessel plying the waters between Scandinavia and Australia. There is also a cosmic-ray station aboard a United States Super-Constellation aircraft which is taking magnetic measurements in the "Magnet" Project.

Through the joint efforts of American, British and Soviet investigators in the Antarctic at the Byrd, McMurdo, South Pole, Vostok, and Halley Bay stations, scientists keep under constant surveillance all bursts of very-low-energy solar protons.

Numerous rockets and artificial satellites are also patrolling the heavens. Instruments carried by space probes are designed for measuring both very low and very high energies of primary protons and electrons. The twelve-ton Soviet satellite Proton 1 launched on May 16, 1965, made

it possible to measure particles with energies about 10^{14} eV and determine the distribution of primary protons within the energy range from 10^{10} to 10^{14} eV. On the earth, this equipment has yielded results only in studies of particles of energy a hundred times less.

We may summarize by saying that the minimum of solar activity coincided with the maximum activity of those studying it. These messengers from deep space will not be able to keep their secrets for long.

The invisible belts of the earth

Everyone knows of the rings of Saturn, but only recently did we learn that our own earth is not devoid of a certain cosmic embellishment. True, the rings, called radiation belts, are not visible in any way, but instruments clearly feel the presence of particles there.

Today nobody considers the earth as consisting only of solid and liquid spheres. No, the lithosphere and the hydrosphere are customarily supplemented by the atmosphere, or the gaseous mantle of the planet. It is clear that the atmosphere is an unalienable part of the earth, for, among other things, it rotates with the earth.

The magnetosphere is just as integral a part of the earth as the other three familiar spheres. Anyone who wants to determine how big our earth is, will have to figure out where the magnetic sphere ends, for it is within this sphere that all events of earth-sun relations take place.

By all rights, the "end" of the earth should be

that limit in space where the earth's magnetic field no longer diminishes with distance from the surface, for here it is no longer the earth's field but the interplanetary magnetic field, which does not depend on distance from the earth.

So the true boundaries of our big home, if taken as a real whole from cellar to roof, pass at a distance exceeding some twelve earth radii.

During the International Geophysical Year no one would be surprised to hear that the earth is under constant bombardment of cosmic rays. Balloons and rockets sent up shortly after World War II showed that at heights of 40 to 50 kilometres above the earth's surface substantial changes occur in the intensity of cosmic radiation, yet there does not seem to be any change at all above this level.

But what about still greater distances from the earth? Here the second and third Soviet Sputniks carried cosmic-ray counters out to distances exceeding a thousand kilometres. Here it was found that the intensity of cosmic radiation begins to increase with distance. The satellites encountered whole swarms of particles when they approached the zone of auroral displays. That was the pattern observed by both Soviet and American satellites.

Analyzing the results of the first satellite measurements of radiation, Soviet scientists headed by S. N. Vernov, Corresponding Member of the U.S.S.R. Academy of Sciences and American specialists working under Professor James A. Van Allen came to the conclusion that we are dealing here with a radically new phenomenon: radiation that the force lines of the magnetic field capture

and do not allow to reach the earth's surface.

Before, scientists had allowed for the possibility of a temporary capture of charged particles by the magnetic field of the earth, as witness the experiments of Birkeland dealing with the motion of charged particles in a magnetic field, or the theoretical calculations of Störmer and the prominent Swedish astrophysicist Alfvén. But at the time that was only a hypothesis. What is more, it was believed that the capture occurred at considerable distances from the earth, the space in the immediate vicinity being a zone prohibited to particles (true, with the exception of the region of polar auroras).

In contrast, today on the basis of a whole series of experiments a theory has emerged stating that the whole magnetic field of the earth is an enormous trap for particles coming from the distant expanses of space. It became quite clear that with this gigantic magnetic net, the earth just sweeps up the little "butterflies" that flit in from the depths of the universe.

It was natural to presume that the distribution of the particles, the radiation in the space about the earth, should depend on the shape of the earth's magnetic lines of force. To verify this and to figure out the dimensions and structure of the radiation zone, it was necessary to measure the radiation out to appreciable distances from the earth.

The first measurements of this type were carried out by the American space probe Pioneer 3 on December 6, 1958. It was fired moonwards, but due to some malfunction returned from a

distance of about 107,000 kilometres. In the process, Pioneer 3 went through the magnetosphere twice (out and back). Its return trip did not go over the same route, but both trajectories passed close to the magnetic equator, and the Geiger counters on board showed variations in the number of charged particles along the way.

The following year, similar measurements were taken three times, in January and September by the Soviet automatic interplanetary stations Luna 1 and Luna 2 and in March by the American space probe Pioneer 4. The results obtained were all very much alike. It turned out that enormous regions of circumterrestrial space, practically the whole magnetosphere of the earth (that is, to the extremes that our magnetic field extends) is filled with charged particles of a range of energies that have been captured and are contained by the earth's magnetic field.

The discovery of this captured-particle region, which goes by the name of "radiation zone", or "radiation belt", is one of the most interesting and most important discoveries of the International Geophysical Year. From the very start it was clear that this belt is directly related to the auro-ras and to magnetic disturbances and that the level of radiation and the shape of the zone may be dependent on the activity of our sun.

Measurements were first made with counters that permitted determining the radiation intensity within comparatively narrow ranges of particle energies. These measurements pointed to the existence of two zones of radiation, two belt reservoirs of particles circling the earth.

When the counter readings of Pioneer 3 were

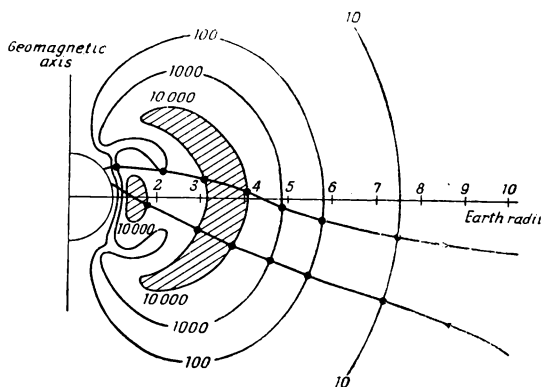
plotted, the curve quite unexpectedly turned out to be double-humped. Out to distances of approximately 10,000 to 12,000 km from the centre of the earth the curve rose sharply indicating an increase in quantity of particles. This was followed by a sudden decline (a trough in the curve). Then when the probe reached 15,000 to 18,000 km, the curve again rose. After 23,000 km, the number of particles went into a smooth gradual decline. On the return leg of the journey, all these events were reversed.

The only thing to conjecture was that each of the humps in the curve denoted an individual region of radiation. The one closer to the earth was called the inner radiation belt, the more distant one, the outer belt. Investigators were first inclined to think that the inner radiation belt was made up of positively charged particles (high-energy protons), and the outer, of high-energy electrons.

However, subsequent experiments demonstrated that electrons and protons are present in both regions. Later, it became clear—although this might have been assumed earlier—that the low-energy particles could be at greater distances from the earth than the more energetic particles because they could be held in by a weaker magnetic field.

Today, scientists incline to the view that the radiation zone that stretches out to the very limits of the magnetosphere is an integral whole. However, the inner portion differs drastically from the outer portion, so we shall discuss them separately.

The inner zone has the shape of a belt sym-



How radiation is captured. Cross-hatched portions indicate inner and outer radiation belts. Labels indicate number of particles counted per second. Data are based on measurements of satellite Explorer 4 and space probe Pioneer 3

metric about the magnetic equator but somewhat shifted relative to the geographic equator. Its lower edge in the western hemisphere lies at about 500 km, in the eastern hemisphere, at 1,500 km from the earth's surface.

The belt circles the earth at an angle (is asymmetric) because the magnetic axis of the earth does not coincide with the axis of rotation. It is displaced several hundred kilometres towards the eastern hemisphere and the swarms of particles obedient to geomagnetism pass lower down in our hemisphere than in the western hemisphere.

The radiation belt is rather wide, extending from the geomagnetic equator northwards and southwards to 45° and embracing a swath over

Central and South America, nearly the whole of Africa, the southern part of Asia, Australia and Oceania. At its thickest, in the plane of the equator, this radiation belt measures several thousand kilometres.

The inner radiation belt is always in a rather calm mood. During a whole year the number of particles inhabiting this region does not change by more than a factor of two or three in either direction. And the location of the belt in space hardly at all varies with time.

This is apparently the result of its comparatively indifferent attitude towards solar activity and magnetic activity. True, a case was observed when a burst of cosmic rays of solar origin boosted the particle intensity somewhat. Apparently, this does not occur so often, and the burst exerted its main effect on the most distant part of the inner belt.

A few words about the composition of the inner belt of the earth. Photographic plates that travelled by rocket to 1,200 kilometres returned with autographs of protons of energy from several tens of millions to hundreds of millions of electron volts. Another rocket related that at 1,000 kilometres out it encountered electrons of energy only about 150,000 eV.

The next problem is of course to find out where these particles come from that fill up the enormous belt-like reservoir. We have to admit that opinions differ: not much time has passed since the discovery of this phenomenon and very little information has been accumulated so far. At present the most widespread view is this.

Cosmic rays are believed to be responsible for

the inner radiation zone. Primary particles coming to the earth from the depths of the universe bombard our atmosphere. Collisions with atoms generate secondary particles which include quite a few neutrons. Since neutrons are neutral, they are not affected by the earth's magnetic field and splash out in all directions. Some move towards the earth, others, away into space.

Now neutrons have short lifetimes, on the average of about 13 minutes. They decay into protons and fast electrons, both of which are charged and cannot therefore ignore terrestrial magnetism. The magnetic field captures them and delivers them to the inner radiation belt of the earth, where they stay trapped for quite some time.

We now turn to the outer radiation belt. From the very first measurements it was evident that there is always a "no-man's land" between the belts, as indicated in the graph by the space between the two humps of the curve. In cross-section, the outer radiation belt is in the form of two half-moons concave to each other. The bent horns reach to approximately 65° north and south magnetic latitude; that is, they come within the zones of auroral displays.

This belt is farthest from the earth over the equator. Here the lower fringe lies at a distance of 12,000 km from the surface. Over the Arctic and Antarctic, the narrow bent horns drop to 250-500 km above the earth.

Now the outer boundary of the outer belt is quite a different matter. It is not easy to determine because we are dealing with captured radiation and its sphere of influence should van-

ish where the magnetic field ceases to capture and hold particles. But this region coincides with the boundaries of the magnetosphere. It is obvious that the boundary line varies with the energy of the particles and will pass at different distances from the earth.

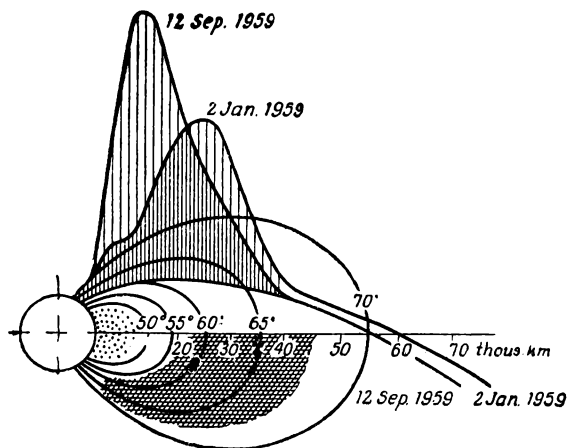
In the first measurements, when counters kept tab only of high-energy particles, it seemed that the outer zone extended to 40,000-60,000 km. But later, when charged-particle traps were employed first by Soviet and then American investigators to measure the less energetic particles, the boundary kept moving away from the earth. At one time it was even believed that there was a third zone made up of low-energy particles and located beyond the outer zone, a sort of outermost zone.

The temperament of the outer radiation belt is not at all so even as that of the inner one. The trouble is that it is all the time doing business with the sun and the magnetic field.

The satellites Injun 1 and Injun 3, orbited at about 1,000 km, passed close to the poles; with a special device they oriented by the magnetic lines of force. They found that in the outer zone there is a considerable diurnal variability in the position of captured particles of different energy. Thus, the northern boundary of electrons with energies exceeding 280 keV was, at local noon, confined to the line of force passing through the magnetic equator at a distance of eight earth radii, while at local midnight, the distance was twenty earth radii. This may be due to the fact that the magnetic field is upset by gusts of solar wind.

What particles inhabit the outer belt of radiation? In contrast to the inner belt, there are very few protons here. Its principal inhabitants are electrons, and their numbers can increase or decrease tenfold in a single day.

The greatest electron intensity is observed in the plane of the magnetic equator at a distance of about 22,000 km from the centre of the earth. Electrons of the outer belt have energies roughly within the range from 40,000 to 5,000,000 eV, so that there is quite some variety here. Most numerous are particles with energies between 80,000 and 1,500,000 eV. In the maximum zone, about a hundred million particles coming from all sides hit a square centimetre every second.



Distribution of captured radiation based on observations of first and second Soviet space rockets (schematic)

There are so few protons in the outer belt that they were not found right off. Only in 1961 were protons detected by the Explorer 12 satellite. So far we have encountered protons with energies only between 100,000 and 4,500,000 eV, but it is suspected that there are protons with higher and lower energies, but not such as in the inner zone.

To summarize, then, the size of this radiation zone is enormous. On the sun-lighted side, it can extend out from eight to thirteen earth radii, on the night side, as far as we can conjecture, out to more than twenty-two earth radii. With the exception of cosmic rays that penetrate the magnetosphere, all the other radiation captured and contained by the magnetic field for long periods forms just as integral a part of our planet as does the solid portion and the gaseous mantle. But no other sphere of the earth experiences such large fluctuations as does the magnetosphere in a single day.

Scientists now feel convinced that the long night tail of the magnetosphere with all the particles therein does not participate in the daily rotation of the earth. It is very likely that only a small portion of the tail (out to eight or ten earth radii) that goes to make up the more or less stable nucleus of the magnetosphere takes part in the earth's rotation. The remainder slips over the nucleus and maintains the same position relative to the sun.

But how do charged particles behave that get picked up by the magnetosphere? One thing is sure, they have no easy life of it. Electrons and protons are constantly hurtling from one end

of the enormous magnetic trap to the other with tremendous velocities, different particles having different velocities.

We do not know how the low-energy particles of the solar wind can penetrate into the depths of the magnetosphere and acquire high energies. So far there are only a variety of suppositions. But we do know that once they have been taken prisoner by the magnetosphere, they are constrained to move and obey the deflecting action of the earth's magnetic field.

If the direction of motion of a particle coincides with the direction of the line of force, it simply slips along it. But if, as is more often the case, the particle enters the field at some angle to the force line, it gyrates down the line of force.

The radius of a spiral traced out by some particle is directly proportional to its mass (this makes the diameter of a proton-turn 1,840 times that of the diameter of turn of an electron) and is inversely proportional to the intensity of the earth's magnetic field in the region that it is confined to. Which means that the higher the latitude the particle enters, the narrower the loop that it makes round the line of force. What is more, electrons loop round it in one direction, and protons in the opposite, and the tiny magnetic field set up by each within the spiral reduces the total magnetic field of the earth at the given point.

The magnetic field increases as it approaches the magnetic poles, thus reducing the radius of the spiral traversed by the visiting particle. At the same time the angle between the line of

force and the direction of motion of the particle increases. Finally, the particle revolves at a right angle to the line of force. Then something like reflection occurs: the direction of translatory motion is reversed, and the particle spins down the spiral along the same line of force to the other end of the earth.

And so on, numberless times, the particle swings down the line of force covering in a second or so the enormous arc from one point of reflection to the other and back again. That would go on indefinitely if all events took place in an absolute vacuum.

But the upper atmosphere is far from an absolute vacuum. Scattered about in profusion are atoms and molecules of gases, and their numbers increase as one approaches the earth. The newcomers collide with particles of the air, lose energy by giving up their charge to neutral particles and perish by absorption in the atmosphere. These collisions are particularly frequent in the bent horn tips of the radiation zone that bring the particles close to the earth's surface where they enter the denser layers of the atmosphere.

Captured particles spill out of the annular reservoir and are scattered in the upper layers of the atmosphere over the far north and the far south of our planet. On occasion, nature immortalizes them with resplendent auroral displays over the icy wastes of the Arctic and the Antarctic. Other events take place at the same time; the upper atmosphere heats up and radio waves are absorbed at an accelerated rate. But that will be described in a later chapter.

Flights along lines of force are not the only motions of charged particles that are captured by the magnetosphere. Such particles are constantly being shifted about; they drift round the earth along magnetic parallels. This is the reason.

The magnetic field of the earth diminishes with altitude. The trajectories of particles spiraling along a line of force are more gradual in the upper part of the spiral and steeper in the lower part. That is what makes a particle shift in a direction perpendicular to the field during each traverse: protons slip westwards and electrons eastwards. This sets up a ring electric current round the earth in a westerly direction. A particle with energy about a million electron volts shifts round the earth making a complete circuit once every 24 hours.

The foregoing is accounted for by a special theory. In 1958 an incident occurred providing experimental verification. In August of that year, a nuclear device was exploded over Johnston Island, a coral island in the Pacific Ocean lying between the Hawaiian and Marshall islands. It was detonated at a height of about 70 km. The result was an unexpected (for it was a secret nuclear test) auroral display in the region of the Samoa archipelago over the Apia Observatory some 3,500 kilometres from the site of the explosion.

This typically polar phenomenon put in an appearance in the tropics not by accident at all. A close look at the magnetic map shows us that the point of explosion and the site of observation of the unusual aurora lie roughly on one

and the same geomagnetic meridian symmetric about the geomagnetic equator: Johnston is north of the equator just about as much as Apia is south of it. They are conjugated by one and the same line of force of the earth's magnetic field. Electrons generated by the explosive force rushed along these rails into the opposite hemisphere triggering a tropical aurora and thus proving the foregoing theory about particle behaviour in the earth's magnetic field.

Several other atomic explosions set off prior to the prohibition instituted by the Moscow Agreement demonstrated that they set up about the earth an artificial belt of radiation in addition to the natural belts that were discovered during the International Geophysical Year. In July of 1962 the United States carried out Operation "Starfish" exploding a nuclear device in the upper atmosphere at a height of several hundreds of kilometres.

The explosion set up an artificial radiation belt at about 3,500 km above the surface, its lower edge being only 350 km from the earth. The satellites Injun 1 and Injun 3 showed that half a year was needed for the number of electrons injected by man into surrounding space to disperse by 15 per cent.

The electrons leaked into the atmosphere mainly from below and from the sides of the belt. Scientists believe that the particles produced by this explosion will continue to be detected, though in diminishing numbers, for a whole decade following the day of the detonation.

Fortunately, none of the countries that have

signed the Moscow Agreement on the prohibition of atomic explosions will carry out any experiments of this kind. Atomic tests contaminate the atmosphere creating a danger to the health and lives of astronauts; they are also an obstacle to studies of captured radiation of natural origin.

The upper layers of the atmosphere in the polar areas are not the only spot where captured particles can leak out. Quite a few are lost in the region of the negative world magnetic anomaly in the South Atlantic. Particles moving along the lines of force emerging from this enormous anomaly should be reflected at lower altitudes where the air density is higher. Actually, however, they are absorbed here. Observations via the Soviet spaceships and satellite vehicles of the Cosmos series carried out at low (about 300 km) altitudes indicate that the intensity of the captured radiation over this anomaly is appreciably greater than in other places on the same magnetic parallels.

The particle leakage from the radiation zone is particularly great during magnetic disturbances. Although as yet there have been no simultaneous observations of how the magnetic field and the intensity of captured radiation vary during magnetic disturbances, the Explorer 6 satellite was able to find out that during a magnetic storm the electron density in the outer radiation belt diminished by 75 per cent and the altitude for maximum number of particles fell by 10 per cent. When the magnetic storm terminated, the electron density again increased and became even higher than before the storm.

The proton density during the storm nearly doubled as compared to normal.

When scientists had analyzed the measurements made by the third Soviet satellite and its American colleague Injun, it turned out that within the auroral zone the stream of electrons with energies between 20 and 60 keV came out to ten million particles per second per square centimetre. Yet the calculations of some workers show that even relatively weak auroras require electron streams tens of times more intense. What this means is that just a few hours of a good auroral display can use up all the energy accumulated in the storehouse of the earth's radiation belt. But actually not a night goes by without auroras shooting up in the skies over the Arctic and Antarctic. Where do these limitless supplies of charged particles come from?

As yet there is no final answer. It seems very likely that the sun is constantly sending particles into the radiation belt, high-energy particles that are captured by the earth's magnetic field. It might very well be that these are particles of terrestrial origin that the magnetosphere has in some fashion accelerated to high energies.

During 1961 and 1962, satellites moving in elongated orbits followed developments beyond the earth's magnetosphere that occurred after solar flares. It was found that Class 2 and Class 3 flares are attended by powerful fluxes of protons over a very wide range of energies: from units to several hundreds of millions of electron volts, the major portion and the greatest intensity of which involved lower-energy particles. Protons

come to earth in two echelons, as it were: an "express" several hours after the flare, and the other—together with low-energy plasma—a day or two later. Satellites established that the sun's chromosphere gives rise to a great many more flares than hitherto supposed; ground-based observatories simply did not record them. Apparently, each of these flares is capable of pumping supplies of protons into the outer radiation reservoir of our planet.

There may yet be another way of adding "solar warriors" to guard posts round the fringes of the earth. When speaking of the solar plasma, one ordinarily and tacitly assumes it to be completely ionized. But recently Chapman and Akasofu started with the assumption that the solar plasma is not completely ionized, that there are more or less substantial quantities of neutral hydrogen atoms present. Being neutral they (like neutrons) are not subject to the action of a magnetic field and can therefore penetrate the magnetosphere to great depths without exerting any effects on its size.

They are then ionized in collisions in the magnetosphere and are accelerated and in this way participate in building up the current layer and the polar auroras. The authors of this hypothesis say that the neutral hydrogen atoms in the solar plasma endow it with new properties and can account for the great diversity of magnetic disturbances.

The problem of the origin of high-energy electrons is much more complicated. To solve it, scientists threw into the fray space probes and satellites put into eccentric orbits. They went

out beyond the limits of the magnetosphere where the flux of solar plasma—the solar wind—blows with a velocity from 300 to 800 km/s.

Here the proton energy was small (about a few thousand electron volts) and the electron energy a mere several electron volts. One of the satellites got a glimpse of particle behaviour in all three regions: outside the magnetic field, on the boundary line (in the magnetopause) and, finally, in the very heart of terrestrial magnetism, the magnetosphere. It was found that in passing through the magnetopause, protons and particularly electrons increased their energy in some way. Perhaps that explains the ever fresh streams of energetic electrons replenishing the supplies of the radiation belts.

But whether that is indeed the case and just how all this takes place is not yet known. Many more measurements are needed to figure out the frequency of occurrence in the radiation zone of protons with energy less than 100,000 eV and greater than 4,500,000 eV. So far we have observed low-intensity protons, and it is still unclear whether they are responsible for certain variations in the magnetic field that occur during magnetic storms. Scientists are about to make a thorough investigation.

To give a definitive account of processes in the radiation zone of the earth we need to carry out many more investigations and measurements at a variety of distances from the earth, in different phases of relations of our earth to the turbulent and quiet sun, in calm and inclement magnetic weather, and over a variety of energy

ranges. As mentioned in the previous chapter, we need co-ordinated investigations of captured radiation and the earth's magnetic field via satellites, and studies of solar and terrestrial phenomena by all possible methods.

There can be no doubt that the period of the International Quiet Sun Year will make a valuable contribution to the study of these invisible belts of the earth that were first discovered in the International Geophysical Year.

When the sky is on fire

Night set in over Rome and it was calm in this great city of antiquity, when suddenly the sky was lighted up by red tongues of flame in the distance. A conflagration to the west of Rome!

Wakened by a trumpet blast, the legionnaires set forth in haste to fight the flames that were raging in the port of Ostia in the mouth of the Tiber. But when the warriors arrived in Ostia they were amazed to find the town in quiet slumber. No fire at all, yet the sky westwards continued to writhe in angry flames.

This was an auroral display that is rarely seen in lower latitudes. The ancient Roman philosopher Lucius Annaeus Seneca described the events that took place about 19 centuries ago in the reign of emperor Tiberius: "At times the sky exhibits a luminosity without motion, at other times it is full of movement. Some of the movements are like a void when there is no

glow under a shining corona, rather like the oval entrance to a cave; others appear like barrels when a large roundish flame is seen moving from place to place or burning motionless; still others are like chasms when the heavens appear to be torn off, ejecting flame that had been hiding in its depths.... Remarkable are those that have the form of fire in the sky. Sometimes they stand high shining among the stars, at other times they lie so low as to be taken for a distant estate or town aflame....”

Of course, inhabitants of the north are not so awestruck, for these are sights to be seen on almost every clear night. The auroras are mostly rather feeble, but at times their light is brighter than that of the full moon, making it possible to read on occasion.

The Russian pomors on the shores of the White Sea, the Laplanders on the Kola Peninsula, the Norwegians, Finns, and Chukchi, the Eskimos of Greenland and Northern Canada were long since used to these suddenly appearing and vanishing night spectacles of light. Yes, and the Maori whose ancestors in remote days sailed to New Zealand on their ancient “kon-tikis” were quite familiar with the flaming sky.

But it is one thing to see and quite another to understand. There were explanations galore for these spectacles in olden days. The ancient Scandinavians believed the northern lights to be the sparkling of the armour of the heavenly Valkyrie warriors flying over the field of battle. More realistically, the Eskimos thought it was simply the light of the hidden sun reflected from distant ice fields.

“Takhu-nui-a-rangi”—great fire—that is the name given the aurora by the Maori, who believed this to be the flame and smoke of fire ignited by their ancestors, whose canoes had been carried off by the winds to the cold southern seas of the Antarctic. In the Middle Ages, European monks who carefully recorded in their chronicles every sign of the skies, depicted the auroras in the form of blood-covered spears and severed heads and predicted disaster such as wars, epidemics, and hunger.

Even in our day polar auroras can be confusing. On February 11, 1958, the auroral display over Canada was so brilliant that the automatic circuit breaker in the city of Toronto that stands ready to economize on electricity “decided” that day was breaking and that it was time to switch off the current in the street-lights network.

Of course, this marvellous play of nature can bewilder not only the barbarian and the ignorant monk, but even the modern man of civilization. Here is the description given by Karl Weyprecht, the Austro-Hungarian Arctic explorer and initiator of the First International Polar Year who wintered over on Franz Josef Land in 1872-1873:

“It is now eight o'clock in the evening, the time of greatest activity of the auroras. Their rays should come on very soon now. There it is to the south near the horizon—a faint arc. Suddenly it rises and spreads out to the east and west, glowing bright and ejecting rays of light. Some of them even reach the zenith.

“For a short time everything seems perma-

ment, then it again leaps into life. Waves of light roll from east to west with tremendous speeds, the lower fringe becomes a dark red and green and shimmers up and down. The rays move faster and become shorter, rising upwards and approaching the magnetic zenith. It is like a race of light rays to the zenith.

"At last the tip is gained and they run out again in all directions: north, south, east and west. Are they moving up or down? Who can say? A sea of flame is flowing out of the centre. What colour is the sea, red, or white, or green? Again it is hard to say. All three colours appear at the same time. The rays have already reached the horizon and the whole sky is aflame.

"Nature is putting on a fireworks that goes far beyond the limits of one's imagination. We listen, for surely such a spectacle must be accompanied by sound. But there is none—all about is total silence. . . . Once again it is bright on the ice, and then all vanishes just as inconceivably fast as it appeared, and the dark night covers everything in black.

"That was the aurora in all its brilliance. . . . No pencil can depict it, no colours suffice to paint it, and there are no words to describe it in all its magnificence."

Such was his description, poetical and at the same time scientifically accurate and laconic; and this was by a man who had seen no small number of nature's wonders.

These cold polar lights come in a great variety of forms and shapes. Scientists in their eternal desire to order things have classified even these fantastic spectacles. But since objective criteria

are scanty and unclear, the classification, like that in the days of Seneca, is based solely on the outward appearance of the aurora.

In preparation for the International Quiet Sun Year, scientists published a special unified atlas of polar auroras. Czech, Argentine, Soviet, Australian, English and American specialists sent in their most characteristic photographs. This has helped to define auroral shapes in a unified fashion at scientific stations throughout the world.

It was agreed to divide all auroras into three basic types: rayed, diffuse, and ribbon-like. The rayed auroras include those in the form of bundles of rays and separate rays scattered about the sky. The family of diffuse auroras includes two forms: separate cloud-like patches (reminiscent of cumulus clouds in moonlight) and a feeble luminosity like a transparent haze or veil covering a considerable portion of the sky. In the third category are auroras in the form of arcs and ribbons. Their characteristic feature is that they have a continuous lower boundary. They may be rayed or homogeneous. Sometimes they consist of separate streamers, as it were. At certain times different shapes appear together, at others, they pass rapidly into one another.

The moods of the auroras are also rather diverse. Some are very active with the brilliance, light and position in the sky changing rapidly. Others are quiescent, staying in place for long periods with the same intensity. Sometimes a quiet arc will persist in the same position in the sky for many hours at a time. Of the active ones, the most nervous are the pulsating auroras: their

brightness varies rhythmically, in "beats" with periods of from a fraction of a second to several minutes.

Auroral intensity can also vary drastically. Ordinarily, in visual observations auroral intensity is evaluated on a four-point scale, one designating the brightness which is comparable with that of the Milky Way, and four, with that of cumulus clouds lighted by the moon or brighter.

Auroras are so diversified that it is often difficult to classify them exactly. Beautiful "curtains", "dancing" rays, effulgent "coronas", "flaming luminosities", spiral-shaped figures and much else await the patient observer if the cold does not chase him indoors. Incidentally, in warmer climes (at lower latitudes), one may on occasion get to see a most remarkable display in these areas—the red aurora. It was probably just such a display that sent the ancient Roman legionnaires on their fire-fighting expedition. By the way, this is a rather rare occurrence, particularly when the sun is quiet.

To understand the nature of the polar auroras, it is very important to know the altitude at which they occur. In the first quarter of the eighteenth century, heights were measured by the method of measuring angles from two points. Such techniques were very imperfect and could not yield exact results. That gave rise to the insistent view that auroras could also be observed close to the earth. Some scientists, including Weyprecht, whom we quoted a little way back, claimed they themselves had seen auroras practically a hundred metres from the earth's surface.

Some observers reported various noises that attended the aurora. But, as one wit put it, the more this phenomenon was watched, the quieter it got. As measuring techniques grew more precise, it became clear that auroras occur at high altitudes.

An exact determination of the altitude of an aurora became possible only in the first decade of this century when first in Norway and then in other countries a method was initiated in which photographs were made simultaneously at two or more sites separated by several tens of kilometres. The altitude of the aurora is found from the shift relative to the background of stars.

Particularly important for auroral theory is a precise knowledge of the lower boundary because it determines the penetrating ability and energy of the particles responsible for this phenomenon. It was found that auroras sometimes are observed 65 to 70 km above the earth's surface. Mostly, however, the lower boundary of an aurora lies at about 100 km. The very highest of auroral spectacles was observed at an altitude of about 1,100 km. This was a luminosity in the form of rays lying in the atmosphere and illuminated by the sun. Just recently this region was believed to be the upper limit of the earth's atmosphere. But the space age and the launching of artificial earth satellites have now demonstrated that the aerial roof of our planet is much higher. In medium and low latitudes, auroras are observed at greater altitudes than in high latitudes.

As to the geographic distribution of polar auroras, it might seem that the question is clear: the closer to the poles, the more frequent they put

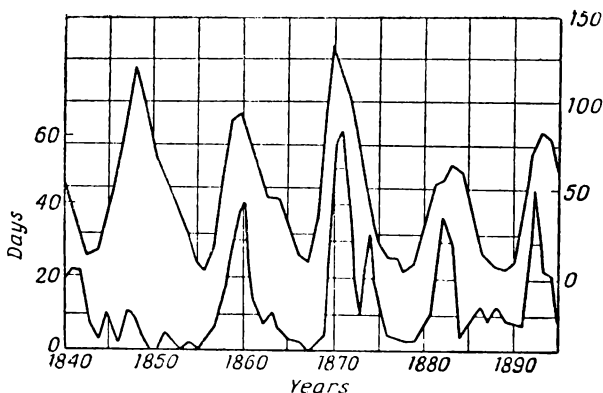
on their displays. Whence the name "polar". Yet this is not so.

When moving from low to high latitudes, the night sights become more frequent. But long before you reach the pole, the frequency of auroral displays has fallen off considerably and diminishes faster than it had increased before. The zone of maximum auroras in the northern hemisphere passes through the northern coastline of Scandinavia, the Kola Peninsula, Novaya Zemlya, Taymyr, Wrangel Island, Alaska, the high-latitude part of Canada and Labrador, south of Greenland and Iceland. Here, during the dark time of the year, nearly every night has a show to offer.

The situation is similar at the other end of the world, in the Antarctic. There the zone of maximum auroral sights passes to the right outside the ice continent and north of the U.S. Byrd station, crosses the coastline of Antarctica near 135° east longitude, and then moves over the waters of the Indian Ocean approaching Macquarie Island of the Australian subantarctic and the French subantarctic island of Kerguelen; then it passes north of the Australian polar observatory at Mawson and completes its round-the-world trip by passing the coastal Japanese Antarctic station Syowa.

It is important to note that the centres of these nearly circular zones are not the geographic but the geomagnetic poles—poles of homogeneous magnetization of the earth. The zones of maximum frequency of auroral displays are distant from the geomagnetic poles by about 23°, which makes their geomagnetic latitude 67°.

If we plot on a map the average number of



Relative sunspot numbers and frequency of auroras keep close step in southern hemisphere. The discrepancy in 1845-1855 is due to irregular observations

auroras observed every year at different places and connect them with lines (which are called isochasms: lines of equal average annual frequency of visible auroras), we get curves with a common centre. And the centres of these curves lie on the geomagnetic pole both in the Arctic and the Antarctic.

The distribution of polar auroras is influenced by the permanent magnetic field of the earth and also by occasional magnetic disturbances. In the absence of intense magnetic disturbances, the auroras appear in a comparatively narrow zone of maximum frequency of their usual visibility, so that those living in the northern hemisphere south of this zone but not far away from it see auroras to the north on such magnetically quiescent

days, while those wintering inside the zone (on Franz Josef Land, on Spitzbergen or on "North Pole" drifting stations) will observe them mostly in the southern part of the sky at this time. Those who live right under the zone, say in Murmansk or Cape Chelyuskin, see them more often in the zenith.

On days of magnetic disturbances, the auroras shrink, as it were, into the lower latitudes. And the more intense the magnetic disturbance, the closer to the equator they are seen. During the IGY when magnetic storms were frequent guests, the auroras were often seen (in the zenith too) at magnetic latitudes less than 40° . There were cases when they lighted up the zenith even at 33° magnetic latitude.

The frequency and intensity of magnetic disturbances vary with the cycle of solar activity. Obediently, the auroras put in an appearance in step. The lights outside the zone are most often visible during years of maximum solar activity; inside the zone—so some observers say—they are more often visible during minimum solar activity. As to the zone itself, the frequency of appearance remains constant, but it might be that the intensity varies. It is highly possible that the auroral zones themselves move a few degrees when passing from maximum to minimum. This may be verified after the materials of the IGY and the IQSY have been correlated.

There are other facts as well that point to a relationship between the auroras and permanent and variable magnetic fields. We know that the rays of the aurora are always aligned with the lines of force of the magnetic field. If the aurora

is high up and comprised of long rays, perspective will make the rays appear to converge in a single point, just like railway tracks appear to meet in a point in the distance. That is how one of the most beautiful displays of the aurora—the corona—is formed. The point of convergence of the rays lies near the magnetic zenith, which is the point of the apparent intersection of a magnetic line of force with the celestial dome.

The arcs of auroras, some of which extend to several thousands of kilometres, lie on the outer side of the auroral zone mostly along the magnetic parallels. During the night their direction may change by as much as twenty or so degrees.

As observations during the IGY have shown, the behaviour of arcs inside the auroral zone is quite different. On the average they are oriented in the direction of the sun, and for this reason their position in the sky can change during a 24-hour period by as much as 360° .

The closer they are to the auroral zone, the more often they appear at midnight local time and the more intense they become. Within the zone there is a second maximum (in addition to the midnight maximum)—during the morning hours. As the latitude of the site of observation increases, it approaches local noon and its intensity increases. At the Amundsen-Scott Antarctic station of the United States, located near the south geographic pole, observations during the polar night have revealed that the frequency of auroral displays at noon maximum proved to be comparable with the frequency at the midnight maximum, though the intensity of the lights at

midnight maximum was roughly twice that at noon maximum. Which means that daytime displays during the polar night must be weaker than nighttime displays. The two maxima of magnetic activity at the Amundsen-Scott station are equal in intensity and coincide in time with the maxima of the auroras.

In the whole world there are about ten people that claim they have seen auroras in broad daylight. Though most of these cases are on days when displays on the night side of the earth actually occurred, nevertheless there has been some doubt as to the veracity of these claims. Some, as we recall, even insist on having heard the sounds of auroras.

In the IQSY, workers had a scanning spectrometer that enabled them to verify the presence of auroral displays in the daytime. A couple of years ago, Canadian scientists reported that they had finally been able to detect daytime auroras with the aid of this instrument.

The spectrometer also proved helpful in carrying out simultaneous observations of auroras at magnetically conjugated points. Up till now such observations were confined to very brief time intervals during equinoctial periods (March 21 and September 23), when day and night are equal to 12 hours over the whole planet, with the exception of the geographic poles.

During the IGY, observations of this type were possible only during four or five days. It was established that auroras were observed at conjugate points simultaneously, but while some pairs of points exhibited displays similar in shape, movement and variation of intensity, others re-

vealed appreciable discrepancies, though on the whole there were similarities.

Peculiarities in the geographic distribution of polar auroras and their close relationship with magnetic disturbances and solar activity have long since suggested that the sun can emit charged particles in addition to wave-type radiation and that such particles are the cause of magnetic storms and auroral displays.

When cathode rays were discovered, it was suggested that the particles coming from the sun might be electrons. As already mentioned, this supposition was the core of the Birkeland-Störmer theory of the origin of magnetic storms and auroras. It was taken that active regions on the sun could expel comparatively narrow, pencil-like beams of cathode rays, which under the action of the earth's magnetic field are deflected into the polar regions and the night side of the earth. Here they collide with particles of the air and give rise to auroras in the upper atmosphere. But we have already mentioned the difficulties this theory experiences when attempting to account for magnetic storms. Explaining the auroras was no easy job either.

For electrons to be able to penetrate to regions where the lower fringe of the auroras actually lies, they must possess energies of the order of tens of kiloelectron volts. But with such energies they would be so strongly deflected by the magnetic field that the auroral zones would be only 3° to 4° from the geomagnetic poles and not 23° away. Now the fact that auroras appear at a distance of 23° from the geomagnetic pole indicates that electron velocities are close to the speed

of light. But if that is the case, electrons would be able to penetrate much deeper and set up auroral spectacles at the very surface of the earth.

To obviate this difficulty, as we have already noted, Störmer assumed the existence about the earth of a ring current whose magnetic field should pull the polar auroras into lower latitudes. However, the ring current, consisting as it does of particles of the same sign (with the same charge) could not have existed for a long time, all the more so in the absence of magnetic storms.

On the Birkeland-Störmer theory, given high electron velocities, there should be an enormous space round the earth in the form of a ring, access to which is forbidden to particles from the sun. But this, as we know, contradicts the discovery during the IGY of the earth's radiation belts.

Another theory, advanced by the prominent English geophysicist Sidney Chapman, is far from an exhaustive explanation of the auroras. Still, it is very successful in showing the possibility of neutral streams, consisting of particles of both signs (protons, ions and electrons), approaching the earth in the region of the geomagnetic equator to distances of several earth radii.

Despite this apparently unsatisfactory situation with the theory of auroral displays, scientists hope that the origin of the northern (and southern) lights will be deciphered within the next few years. This hope rests on the fact that today we can carry out direct observations, via satellites and rockets, of the earth's magnetosphere, solar

streams and their interaction with the magnetic field of the earth.

Another important peculiarity of the aurora is its spectrum. According to the latest thinking, auroras are a fluorescent luminosity of atoms and molecules of the air in the upper atmosphere that become excited in collisions with fast charged particles, mostly electrons and protons. At one time it was thought that these particles come to us directly from the sun. Today we know that a portion of them, if not all, are taken from the resources that are constantly building up in the outer radiation belt of the earth.

The ability of rarefied gases to fluoresce under the action of electrically charged particles is widely utilized today: fluorescent lamps, the varicoloured neon lamps of city advertizing. Yes, all these inventions are simply tamed northern lights, close kin to the real auroras of the Arctic and Antarctic. Here both nature and man take advantage of the property of certain gases to glow when electric charges are passed through them.

But man has outwitted nature. There is a double transformation of energy in fluorescent lamps: first electrons emerging from a cathode make the gases in the lamp emit an invisible ultraviolet light, which in turn makes fluorescent substances that coat the walls of the lamp glow with a visible light.

One of the first to explain the auroras as an electric discharge in gases was Mikhail Lomonosov. In 1753 he addressed the Academy of Sciences of Russia with a "Word on Aerial Phenomena that Originate from the Electrical Force". He said: "It is highly probable that the northern

lights are generated by an electrical force originating in the air. This is confirmed by the similarity of the appearance and disappearance of movement, colour and form that is observed between the northern lights and electrical light. . .”

Hypotheses attributing the aurora to an electric discharge in gas continue to be advanced by many workers to this day, but of course on a different scientific basis. Auroral spectra may be studied both in their visible portion and in the invisible ultraviolet and infrared regions. They consist of individual lines and bands; this indicates that they are emitted by both atoms and molecules of gases of the atmosphere.

Auroral spectra tell us about the gaseous composition of the atmosphere and its distribution up to considerable heights. They also make it possible to gauge the temperature in the upper layers of the atmosphere.

Spectra indicate that auroras are generated mainly by the radiation of neutral and ionized atoms and molecules of oxygen and nitrogen. For example, atomic oxygen in an excited state emits an intense green line, which accounts for the greenish colour of ordinary auroral displays. The completely red auroras observed in the lower latitudes during years of maximum solar activity are also caused by the emission of atomic oxygen.

However, opinions differ about the reddish colour of the lower fringe of certain arcs mostly observed during minimum solar activity. Some believe that they are caused by the emission of oxygen molecules, others say nitrogen molecules. Both may be right and the two effects may be present together.

The composition of an auroral spectrum and the relative intensity of the individual lines and bands vary greatly from aurora to aurora depending on the shapes, altitudes, and the latitude of the locality where it is observed. Spectra have demonstrated that in addition to molecular nitrogen and oxygen in the upper atmosphere there are large quantities of atomic oxygen and nitrogen as well. They point to the presence of hydrogen and helium in the upper layers of the atmosphere.

The existence of hydrogen in the upper atmosphere was first established in 1949 when the auroral spectrum was found to contain emission lines of hydrogen. Observations of these lines in the magnetic zenith demonstrated that they were broadened and displaced towards the ultraviolet end of the spectrum, which indicated the Doppler effect; this meant that the particles were moving along lines of force towards the earth with a velocity about several thousand kilometres per second. At this speed, they should have energies of the order of hundreds of kiloelectron volts.

It was supposed that they were particles of extra-terrestrial origin and that they came to us from the sun. Today we know that during solar flares the sun expels powerful fluxes of protons of various energies and that such protons are found in the radiation belts of the earth.

Not so long ago it was found that auroral spectra constantly exhibit weak hydrogen lines, which correspond to hydrogen atoms of energy not exceeding a few tens of electron volts. This supports the view that there is atomic hydrogen in the upper atmosphere. There is also helium of

terrestrial origin in the upper layers of the atmosphere. This has been confirmed in recent rocket probings.

There is no definitive theory of the formation of auroral spectra, but certain peculiarities have laid bear a few secrets. Rays hundreds of kilometres long and only a few hundreds of metres across, arcs and ribbons with thicknesses that do not exceed a hundred metres suggest that only high-energy charged particles moving in spirals around the magnetic lines of force can be the source of ionization. This is again supported by the fact of enhanced ionization along the rays in addition to excitation of atoms and molecules of the air.

Among the first to detect this ionization were short-wave radio hams who demonstrated that communications can be maintained by very short waves via reflection from auroras. For scientists this means the possibility of radar probing of the aurora on frequencies between 20 and 800 MHz (megahertz, or megacycles per second). Radio reflections from auroras are obtained only if the radar wave is sent perpendicular to the magnetic lines of force.

The ionization is distributed along the magnetic line of force with the auroral ray, since only in this case can the waves, which are reflected at right angles from the ionized region, return to the radar receiver. For this reason, radars in the north do not record auroral displays visible in the zenith or in the south, or at an angle of a few degrees to the magnetic meridian.

In view of the fact that the mass of the proton is greater than that of the electron, the latter pos-

sesses a considerably greater penetrating ability than protons of the same energy. Approximate calculations show that to reach an altitude of 100 km, protons need an energy of the order of 200keV, while electrons need only 10 keV.

Rocket measurements in the auroral region have, at about 200-km altitudes, detected electrons with energies of the order of tens of kilo-electron volts and protons of hundreds of kilo-electron volts. Earlier rocket measurements established that in the auroral zone from 40 km upwards there is an intense X-radiation due to the deceleration of electrons in the atmosphere.

Thanks to satellite measurements we know that particles of sufficient energy to produce an auroral display are found in the radiation belts. The question is: Do protons or electrons cause the aurora?

Auroras are now under constant surveillance as never before during earlier minima of solar activity. Tens of stations in the Arctic and Antarctic are constantly taking photographs of auroras during the dark time of day (or year) with ingenious all-sky cameras. The camera looks down into a convex mirror that reflects the whole sky from horizon to horizon.

Photographic observations of the aurora are supplemented by round-the-clock observations by means of radar, which detects displays in any weather. Dozens of high-sensitive spectrographs record the spectra of polar auroras. In medium latitudes hundreds of weather stations on hour-by-hour observations round the clock are also handling auroral observations.

All this will provide invaluable material for

compiling hourly maps of the visibility of auroras and maps of isochasms, and also for studying the relationship between auroras and magnetic disturbances and for many other problems.

Officers of the watch on ships crossing the North Atlantic, navigators aboard aircraft flying from Europe to America and back have also become hunters of auroras.

Extensive investigations have been carried out on satellites and rockets. Rockets with scanning spectrometers have made possible the study of auroral emissions in different sections of the spectrum, including those emissions which do not reach the earth's surface because of absorption. Satellites will be employed for photometric observations of auroras and for measuring the composition and energy spectrum of particles that give rise to the aurora.

It is highly encouraging that the IQSY initiated auroral observations in outer space. Honour for this work goes to the glorious crew of the Soviet spaceship Voskhod, V. M. Komarov, K. P. Feoktistov, and B. B. Yegorov.

Some, after reading this chapter, may have doubts as to just how important all this is. The aurora is undoubtedly a beautiful spectacle, but is it so necessary to send scientists to distant northern lands in order to unravel the secret of this colourful "incorporeal spirit"?

Indeed it is, because the most noble of all human passions—the passionate striving towards "pure" knowledge—has, ultimately, always been the most significant in everyday economic, cultural and scientific activities.

And the aurora, as is now evident, is closely

tied up with laws governing radio waves, with the whims of magnetic storms, which affect compass readings, and with conditions in near space where man has already taken his first steps.

Suffice it to recall the discovery of hydrogen and helium in the upper atmosphere that stemmed from studies of auroral spectra. These discoveries completely changed our picture of the structure of the upper atmosphere. Perhaps subsequent investigations, when we learn more about the formative processes of the auroras, will open up a wonderful window into deeper space.

That is why the radio operator trying to connect up with a distant wintering party and the geologist blazing a fresh trail in the taiga and the spaceman in orbit are all indebted to those who study the mysterious "night fires".

Invisible celestial light

The aurora has been familiar to mankind since time unremembered. But these cold northern lights have a "relative" that has been hiding from us for a long time. It is called airglow.

At the end of last century the English astronomer Campbell, while analyzing a spectrogram of the night sky obtained in a long exposure, noted a strange green line. But there had been no auroral displays. Then the total brightness of the night sky was measured. It turned out to be greater than that which could be produced by all the stars taken together without any outside help. What could it be?

An investigation showed that it was an independent glow in the atmosphere. It was too faint

for the human eye, which is quite natural since its intensity is equal to roughly a millionth part of the lunar light, and that is not more light than a candle sheds at a distance of ten metres. The aurora can be 10,000 times brighter than the newly discovered luminescence. This light comes to us all the time, round the clock; only in the daytime it is completely lost in the sun's rays.

Unlike the auroras, this phenomenon is constant and universal, that is, it is found everywhere and not only in the high latitudes. That is why at one time it was called a non-polar glow or constant glow.

What is the origin of this airglow? It is related to the polar lights and is also generated by light given off by molecules and atoms of gases that make up the upper atmosphere. The origin is similar and so are the "fingerprints": the spectra of the aurora and of the night airglow are very much alike. However, there are differences: the distribution of intensity of the glow in different parts of the spectrum is not the same. Hence, the mechanisms of excitation of the aurora and glow must be different.

There are three types of airglow: night airglow, twilight glow and day glow. We have already touched on the night airglow. It may be added that obtaining reliable results is a difficult job because scientists have to separate out the airglow from such strong interference as starlight, the auroras, and the zodiacal light, which comes from the scattering of the sun's rays on minute particles of cosmic dust.

Observations have shown that principal in the night airglow spectrum are the emissions of mole-

cules of oxygen and nitrogen, atomic oxygen and the hydroxyl OH, with atomic oxygen playing the main role in the visible part of the spectrum. The spectrum of night airglow also exhibits lines of hydrogen.

It is not so easy to determine the substance responsible for the appearance in the spectrum of the night airglow of some band or other, and many of them have not even been caught yet, although the hunt has been on for half a century already. G. MacLennan scored a big success in 1924, when he succeeded in "taking" just such a green line as is observed in the night-airglow spectrum and "putting" it into a laboratory gas-discharge tube.

It was found to be due to a very unstable (metastable) state of excitation when the oxygen atoms can pass into a less excited state with the emission of a green line only under conditions of a more rarefied medium and infrequent particle collisions. These are precisely the conditions that prevail in the upper atmosphere. A metastably excited atom will not emit light under ordinary conditions; it will simply collide with other particles and transfer to them the excess energy before emission can take place.

We cannot say that the glow is uniformly distributed over the whole sky. Brighter regions have been detected, something in the form of glowing clouds moving over the sky. That being the case, they can serve as an excellent means for gauging the direction and velocity of the atmospheric movements at altitudes in the vicinity of a hundred kilometres where nature puts on this display quite invisible to the naked eye.

Another participant is the non-stable molecule of the hydroxyl group OH. The hydroxyl emits most intensely in the infrared part of the spectrum and not in the visible part. If human vision could respond to such radiation, the night sky would be invisible because the infrared glow would swamp all the starlight.

Where does this excess energy come from that the excited particles of rarefied gases carry with difficulty and give up in the form of emission? Naturally enough, the source is again the sun.

Throughout the day the sun spends the energy of its ultraviolet and X-radiation on ionization, dissociation, and the excitation of atoms and molecules of the air. In the upper atmosphere, large quantities of ions and free electrons are formed, the molecules of oxygen and nitrogen are to one degree or another dissociated into separate atoms, and a substantial portion of the molecules and atoms become excited. The temperature in the upper layers of the atmosphere rises.

At the same time, reverse processes are in operation: the excited atoms and molecules of the air re-emit light and return to the normal unexcited state, ions and electrons recombine to form neutral particles, and separate atoms—via various chemical reactions—form into molecules.

These processes continue after sunset. The energy stored in the daytime is released at night in the form of a glow of the atmosphere, which attempts, in a way, to take the place of the sun.

In addition to these cloud-like diffuse glows of the night sky, which are usually formless, the tropics exhibit arc-like glows as well. These arcs

have been found to pass either side of the magnetic equator at a latitude of about $\pm 12^\circ$ and practically encompass the whole globe. Their exact height has not yet been established, but it lies somewhere between 250 and 400 km. Since the magnetic and geographic axes of the earth do not coincide, the arcs are inclined to the geographic equator and occupy a northernmost position in Africa and a southernmost one in America.

The intensity of the arc glow varies with the season in the appropriate hemisphere. Thus, the northern arc located in Africa near the Tropic of Cancer is observed here only in the winter time, the southern arc is seen the year round. In South America the picture is reversed: the northernmost arc is observed the year round, while the southern one is seen in the southern hemisphere only in winter.

The dominant role in the inter-tropic arcs is played by atomic oxygen revealed in spectrograms by special lines. Although the spectrograms also have a green line, the red is predominant.

During a single night the intensity of different component parts of the glow—its colours—can vary by tens of per cent, while from night to night the change is still greater, sometimes several-fold. How is the intensity affected by the level of solar activity? Today it has already been established that the sun handles the green oxygen line with a strong hand, while the other parts of the spectrum either do not change at all or change but slightly.

But all of this has yet to be verified with great care. Neither is there an answer to the question

about the mechanism of excitation of atoms and molecules that cause these phenomena. There are of course quite a number of hypotheses but none seems to give the full answer. In this field we seem to be guessing mostly. That is why studies of the night airglow (both diffuse and in the form of inter-tropic red arcs) occupied such a prominent place in the programme of the IQSY.

The situation is better as regards twilight airglow, that is, we know more about it. In the early morning hours when the lower layers of the atmosphere are still in the dark and the upper layers are gradually coming into sunlight, the spectrum of the sky begins to exhibit lines and bands caused by fluorescence of atoms and molecules under the direct action of the sun's light. Scientists know exactly at what minute the light of the sun will fall on a given part of the atmosphere and how the boundary line of light and shade will shift and, hence, how the height of the radiating layers will change. The evening twilight airglow is quite analogous to the morning glow, but it develops in the reverse order: as the sun sets, the first to cease glowing are the lower layers of the atmosphere, then the upper layers.

Twilight glow was first discovered about 30 years ago. Today we know that its spectrum is largely similar to that of the night airglow. It contains bands of ionized molecules of nitrogen and an intense red line of atomic oxygen. Many discoveries have been made in recent years. Lines of helium, hydrogen, calcium, lithium and other alkali elements have been detected. Of particular interest is the yellow line which indicates the presence of atomic sodium.

It would seem that sodium has nothing to do there in the upper atmosphere. To find it and measure it, rockets have been sent aloft; they have confirmed that sodium "nests" between 70 and 90 km. When the sun is just below the horizon for an observer on the earth, part of the upper atmosphere is already (in the evening: "is still") illuminated. It is then that the atoms of sodium scattered up there avidly absorb radiation attuned, as it were, to sodium. When "sated", they become overexcited and begin intensively to emit energy in all directions. Each atom of sodium behaves like a tiny mirror with the special property of reflecting only yellow light and letting all other light pass through it.

The level of absorption and radiation of this element is known and it has been used to calculate how much atomic sodium is "suspended" in the upper atmosphere. It turns out that at 80 km above the earth sodium comprises one-million-millionth of the atmosphere. Even in our age of infinitely small and infinitely large numbers, this degree of precision merits special respect.

And still, small though the quantity is, we cannot evade the question of where this sodium comes from. This book has no answer. In fact, at this writing the debate continues between supporters of the most contradictory of hypotheses.

Some believe that sodium was brought up from the earth's interior during volcanic eruptions. Others maintain that it is of oceanic origin, that minute particles of spray of salt sea water during storms were carried up into the upper atmosphere by ascending currents of air. Still others claim that it is again the work of the sun: sodium, like

hydrogen, is a solar messenger that has traversed interplanetary space. Finally, some investigators think that sodium was brought to the earth by meteors that burn up in the atmosphere via friction between 80 and 120 km altitude.

At any rate, the last possibility to answer this question is at hand. In a few years it may be too late. The point is that during the past ten years a technique has increasingly been used to study the upper atmosphere that involves observing the glow of sodium vapour delivered to the upper layers of the atmosphere by rockets. The amount of man-made sodium thrown into the upper atmosphere may already have exceeded the natural concentration (which is only a few sodium atoms per cubic metre of air) or will do so very soon. It may very well be that the IQSY represented that last possibility for studying variations in the intensity of sodium glow in the upper atmosphere during the cycle of solar activity.

As for sodium's alkali colleague lithium, which was found in the upper atmosphere during the IGY, its presence is apparently due completely to human intervention. This low-melting-point element is utilized in atomic-bomb casings. In thermonuclear explosions its particles together with the cap of the most poisonous of "mushrooms" are thrown aloft where they make their contribution to the glow.

There now remains the day glow, of which so little is known that there won't be much of a story. The first successful measurements of day glow by means of spectrometers were carried out in 1962-1963 at ground-based stations, in balloons and by rockets. Five lines were found belonging

to atomic oxygen and atomic and molecular nitrogen.

It is supposed that the source of day glow, like that of the twilight glow, is the fluorescence of atoms and molecules of the air under the impact of solar radiation.

The day glow was studied on a broad scale for the first time during the International Quiet Sun Year. Though, as we have already pointed out, this glow is not so closely associated with solar activity as its relative the aurora, its study during the IQSY is of exceptional interest for an insight into phenomena in the upper atmosphere. The point is that spectral studies of it enable us to determine the gaseous composition of the atmosphere and to obtain necessary information about elementary processes and chemical reactions at high altitudes. Utilizing the spectra of hydroxyl, one can determine the temperature in the upper layers where this emission is generated.

During the Quiet Sun Year there were fewer auroral displays and this made it easier to observe the other more modest glows in the higher latitudes. Ground stations scattered round the world carried out photometric studies of the night airglow with special apparatus. Since the airglow occurs at 100 km and higher, each station can keep under control all the space out to a radius of 1,000 km.

Certain countries measured the night airglow on ships and aircraft to check latitude variation. Research rockets have penetrated into the realm of the inter-tropic red arcs to determine the distribution of glow in altitude. When ground stations participating in the IQSY were located at

relatively close distances (several tens of kilometres apart) their observations of the travel of "glowing clouds" indicated the speeds and directions of winds in the upper atmosphere without the launching of expensive rockets.

The cold and lifeless world of the upper atmosphere—this jumping-off spot into outer space—is more and more attracting explorers of the space age. But let us not forget that the first to relate about these regions were the auroras and the airglow.

The ionosphere

At the beginning of the century, in 1901, the Italian inventor Marchese Guglielmo Marconi was first to achieve a radio link-up between England and America. And though the wireless telegraph had been in operation for a number of years by then, this was a remarkable attainment: one could communicate across thousands of kilometres and not just a dozen or so.

"But that is fundamentally impossible!" said some. "Radio waves, like light, are propagated in straight lines. What about the curvature of the earth's surface? Radio waves are unable to curve with it and have to go off into outer space at a tangent where the earth curves." The remarkable thing was that it was a fact: wireless communication over enormous distances was possible. Theorists now had to catch up with practical events and find some explanation for this "wonder".

An American electrical engineer, Arthur Kennelly, and an English physicist, Oliver Heaviside,

the very next year and independently of one another concluded that long-distance propagation of radio waves is possible because of a conducting ionized layer round the earth that is capable of reflecting such waves.

The reader already knows that such a hypothesis was advanced as early as 1882 by the English physicist Stewart Balfour to account for diurnal magnetic variations. But, as is often the case, it was thoroughly forgotten and the still hypothetical ionized region of the atmosphere was called the Kennelly-Heaviside layer. The term ionosphere came into use only in the 1930s after its existence had been experimentally confirmed.

Now we know that in the upper atmosphere, from about 60 km onwards, there is a region with heavy concentrations of ions and free electrons that is capable of scattering, refracting and reflecting radio waves striking it. That is how the waves cover thousands of kilometres round the earth in multiple jumps up and down between the ionosphere and the ground.

But how could a region like that come to be formed with such large quantities of ions and electrons? The most natural thing, the reader will think, is to suppose the sun. Which is all too true.

The basic cause of ionization of the upper layers of the atmosphere is the ultraviolet and X-radiation of the sun. When absorbed by the atoms and molecules of the air, it excites them raising the electrons in the outer shells of the atom to higher levels. It can even tear out some electrons, thus ionizing the atoms. This photoionization gives rise to electrons and positively charged ions.

Electrons can stick to neutral atoms and molecules and convert them into negative ions. There are other sources of ionization too: cosmic rays and, in the higher magnetic latitudes, the corpuscular radiation of the sun.

Ionization is accompanied by the reverse process of recombination, when positive ions and electrons combine to form neutral particles. The rate of recombination grows with the number of free electrons, and when it is equal to the rate of ionization, the electron density does not increase any further.

However, the slightest change in the intensity of the ionizing agents upsets this dynamical equilibrium and the electron density either increases or decreases. That is how the upper ionized layers of our atmosphere are formed that consist of neutral particles, positive and negative ions and free electrons. The refraction and reflection of radio waves from the ionosphere are mainly affected by the light-weight electrons, which in this respect are thousands of times more effective than the slower and heavier ions.

From what has been said it is clear that variations in the ionosphere are associated with the height of the sun above the horizon. The ionizing stream coming from the sun is most intense at noon when it falls straight down and penetrates to a great depth in the atmosphere. At night when the basic ionizing factors are not operative and recombination and attachment of electrons to neutral particles continue, the electron density falls off. This process is fastest in the lower layers of the ionosphere where the air density is greater and particle collisions are most frequent. This

generates diurnal variations in the electron density of the ionosphere. Superimposed on them are variations due to the season of the year, the latter being caused by different orientation of the earth relative to the sun (the source of all trouble) during the seasons.

But that is not all. Solar activity, eternal and temperamental, is yet another factor that affects the behaviour of the ionosphere. During maximum solar activity, in the period of the active sun, the electron density in the ionosphere is higher than during minimum activity, when the sun is quiet. This is true whether or not the sun has any active features on it on any particular day.

Other factors greatly influencing the behaviour of the ionosphere are solar flares, magnetic storms, and the auroras. In a word, then, to predict the state of the different layers of the ionosphere and, hence, the conditions of radio communications requires knowing a multitude of disparate factors.

We have been using the word "layer" although measurements of electron density by rockets show that the ionosphere is no layer cake, rather a unified continuous region with several peak densities of free electrons in altitude. But firstly the terminology is quite established. And secondly—this is probably the most important factor—many phenomena in the ionosphere develop at different altitudes so differently that the division into layers or regions is justified.

It is customary to designate as the *D* layer of the ionosphere that between 60 and 90 km from the earth. Above, all the way up to 160 km, is

the *E* layer, higher still and out to the very beginning of "outer space" is the *F* layer.

Strange as it may seem at first glance, we are least of all familiar with the *D* layer, closest to the earth. This will become clear when we discuss the techniques of investigating the ionosphere.

The most common method of research is the same as that first used in 1925 in the experiments that proved the existence of the ionosphere. It is called vertical sounding and differs from ordinary radio transmission in that the transmitter of an ionosphere station radiates vertically upwards and not at a small angle to the horizon, and in very brief pulses of duration less than one ten-thousandth of a second.

The transmission is conducted on gradually varying frequencies on wavelengths from a tenth of a metre to thousands of metres, the whole range being covered in a fraction of a minute. The pulses reflected from the ionosphere are picked up at the ionosphere station by a receiver that keeps step as the frequency varies in accord with the frequency radiated by the transmitter.

As a result we obtain curves that indicate the height of the reflecting layers from the time it takes the pulses to make the round trip to the ionosphere and back. Taking the speed of radio-wave propagation to be that of light, we get the "apparent" altitude of the layers. It exceeds the true height because the rate of propagation of radio waves in an ionized medium is somewhat less than the speed of light.

The higher the frequency of a radio wave, the higher the electron density needed to reflect it.

Vertical sounding makes it possible to determine the greatest, or critical, frequency that will be reflected from a given layer. Knowing the frequency, we can find out the maximum electron density of the layer, since it will be proportional to the square of the critical frequency.

The *D* layer lies in the depths of the ionosphere. Ionizing radiation is highly attenuated by the time it reaches this region because a goodly portion of it has been spent on ionizing the higher layers. But, as we have already noted, the rate of recombination and electron attachment is highest here. That makes the electron density in the *D* layer low, so very long wavelengths are needed to obtain reflections from it. This requires powerful transmitters and enormous antennas that are not always available. That is why the closest layer is the least studied one. More or less complete information about the distribution of electron density in this layer was obtained only in recent years by rocket studies.

Although the *D* layer cannot reflect medium and short waves, it exerts an appreciable effect on their propagation due to the fact that it weakens them by absorbing a portion as the waves move upwards to higher layers and as they return to the earth after reflection. Some of the energy of the waves goes to putting free electrons into oscillatory motion, which is immediately lost in collisions with the heavier ions and neutral particles.

The larger the number of free electrons that appear in the *D* layer, the more energy the radio waves lose. And the longer waves lose more energy than the shorter ones do. At night the *D*

layer vanishes completely, making reception of short- and medium-wave stations at night better than in the daytime.

To facilitate continuous observations of the behaviour of the *D* layer, a network of radio-metric stations has in recent years been set up to record the intensity of radio noise coming to us from the Galaxy. Since the Galaxy has more than one centre of such emission, the antennas of radio receivers are aligned with the celestial axis pointing to the Pole Star, to that part of the sky that does not change position during the diurnal rotation of the earth. Recordings are made on metric waves that are able to pass through the ionosphere and are yet noticeably susceptible to absorption.

Above the *D* layer is the *E* layer. In the daytime, ordinary ionosphere stations systematically detect it, while at night it is so weak as to be detectable only by special observatories operating on very low frequencies.

This layer has one peculiar whim. Ordinarily, the electron density here varies very systematically with the zenith angle of the sun. But on occasion, and quite unexpectedly, the electron density may turn out greater than expected. Then one speaks of an anomalous or sporadic ionization and an anomalous or sporadic *E* layer.

There are many varieties of this sporadic layer. At times it may be so dense that it completely shields the above-lying layers. Then fonograms exhibit only reflections from this layer. Sometimes, despite the fact that the critical frequency of the sporadic layer exceeds the critical frequencies of the upper layers, it may be so transparent

that radio waves can "see" what is going on above it. The lifetime of the sporadic layer fluctuates from a few minutes to several hours. In high latitudes it puts in an appearance mostly at night, near the magnetic equator, on the contrary, mostly in the daytime.

As soon as an intense sporadic layer appears, radio-wave propagation goes berserk. For example, without any re-transmission, TV broadcasts are picked up very much beyond the limits of direct visibility. During such periods, Voronezh or Odessa picks up TV programmes from stations in Central Europe. All the credit for this goes to the helpful though very wilful sporadic E layer that knows how to reflect waves in the metric range, which television operates on. Unfortunately the lifetime of this layer is very short.

It is not clear yet how the sporadic layer originates. Just a short time ago it was suggested that the layer is produced in eddy-like motions created by winds in the ionosphere. Rocket measurements in one instance revealed a sporadic layer only a few kilometres thick.

The F layer above the E layer lives a "dual life": at night it is unified, in the daytime it breaks up into two layers (F_1 and F_2). This split personality is especially marked in the summer of the appropriate hemisphere and during minimum solar activity. The International Quiet Sun Year is just the right time to study this interesting peculiarity of the F layer.

This layer is tied up with geography too. The daily variations of critical frequencies along some circle of geographic latitude are the same if regarded from the standpoint of local time. And

the behaviour of the F_2 layer is in addition dependent on the longitude of the place.

No less remarkable is the "equatorial" anomaly detected by the English radio physicist Edward Appleton, who was one of the first to study the ionosphere. He found that at equinox at local noon when the sun is in the zenith over the equator, the highest critical frequencies do not occur at the equator but on both sides of it, at geomagnetic latitude $\pm 20^\circ$. Contrary to expectations, in summer the critical frequencies are lower than in winter. In a word, the F_2 layer is full of surprises even when the ionosphere is calm.

When the enormous magnet on which we live experiences big disturbances due to the sun, magnetic storms always exert an effect on the ionosphere. And this is particularly true of the F_2 layer. During such periods, its height increases. The critical frequencies diminish everywhere with the exception of the near-equatorial region, where they increase. During storms, reflections from the F_2 layer become diffuse: they come, as it were, from a variety of altitudes at the same time.

We may take it that there is a rise in temperature in the F_2 layer during magnetic disturbances, which makes it expand and rise to greater altitudes. This would seem to find confirmation in the more rapid deceleration of satellites in the atmosphere at just the height of this layer.

No perceptible changes occur in the F_1 layer and particularly in the E layer during storms. The most intense ionospheric disturbances come in the high latitudes round the polar caps and in the vicinity of polar stations. It is believed that the intense diffuseness of the ionosphere here dur-

ing magnetic disturbances is caused by the intrusion of charged particles.

During magnetic storms radio waves are more intensely absorbed in the ionosphere. And so there is nothing remarkable in the fact that intense magnetic storms are always attended by disruptions in radio communication.

Quite different are the ionospheric disturbances that occur during intense solar flares. The upper layers are not greatly affected, but ionization in the *D* layer and the attendant absorption become so strong that for a time the layer completely swallows up short and medium waves moving into the upper ionosphere. Short- and medium-wave communications over long distances cease completely on the whole illuminated side of the earth. This is a total "eclipse" of the ionosphere. Sudden ionospheric disturbances caused by solar flares may persist for many minutes and even up to an hour.

Three types of absorptions associated with solar flares are observed in the far north and the far south. Some occur suddenly, as soon as there is an intense flare-up in the sun's chromosphere. A solar flare of this kind can act on the ionosphere only when it faces the sun, that is, during a polar day.

A second type of absorption sets in a few hours after a solar flare, which means that solar protons are arriving on the earth. This kind of absorption can occur at the same time in the Arctic and the Antarctic, but only at high magnetic latitudes, above 60° - 65° . It is most intense in the summer hemisphere.

Finally, the third variety does not extend to

the very close polar regions. It is most intense in the zone of polar auroras and commences a day to a day and a half after a flare, when the slower particles have traversed the sun-to-earth distance.

The most elementary theory of ionization of the atmosphere by solar radiation states that if the radiation were monochromatic (that is, if it consisted of waves of the same length) and the atmosphere were homogeneous in composition, we would have only one maximum of ionization. Indeed, the radiation would be most intense in the outermost shell of our planet where the sun throws its unattenuated stream of radiation on our atmosphere.

However, the atmosphere here is highly rarefied. It contains so few particles that the solar radiation finds nothing to collide with. Though the sun tries hard to build up a dense ionosphere, there just isn't material enough here to do it.

Closer to the earth's surface there is an abundance of building materials. But by that time the radiation is quite attenuated, having been absorbed by the denser layers of the atmosphere. Hence the maximum ionization is found somewhere in the middle where the radiation is still energetic enough to knock electrons out of atoms and molecules, and the number of particles suffices to generate large numbers of free electrons. One should of course not lose sight of the processes of recombination and attachment, which reduce the density of the ionosphere as the density of the atmosphere increases.

Actually the real distribution of ionization is much more complicated than described by this elementary theory. At the surface of the earth

the atmosphere is hardly at all ionized. The number of neutral particles in a single cubic centimetre of air about us comes out to one followed by a tail of nineteen zeros. Now the number of charged particles (positive and negative ions) does not exceed a few thousands.

At about 60 km above the earth the situation changes. Here each cubic centimetre of air has 10^{15} neutral particles, which is 10,000 times less than at the earth's surface. And there are substantially more charged particles: up to 10,000 free electrons per cubic centimetre. This is the beginning of the ionosphere, its *D* layer.

At 90 to 110 km above the earth there are still fewer neutral particles, and the number of zeros in our number falls to twelve. The number of free electrons increases tenfold compared with the *D* layer. This is the maximum of the *E* layer.

But the real playground of free electrons is a bit higher in the *F* layer. Here the number of neutral particles falls off again and charged particles build up to a million per cubic centimetre. But the difference is great: there are still a thousand to tens of thousands more neutral particles, so that the plasma here cannot be termed highly ionized.

It is only in the higher spheres, somewhere between 1,000 and 3,000 km up that equality sets in: the number of charged and uncharged particles (the former increasing and the latter falling off) is about the same. Both come in quantities of tens to hundreds of thousands per cubic centimetre. What occurs at 5,000 to 6,000 km above the earth is only now being studied, and we shall take it up a bit later.

How does this complex distribution of ionization in the atmosphere arise? As yet we do not know and there isn't even a generally accepted hypothesis—only a few more or less substantiated conjectures that are waiting for experiments of confirmation and verification.

It is thought, for instance, that ionization in the *F* layer is the result of complicated photochemical and photoelectrical reactions brought about by absorption of hard ultraviolet radiation of the sun that lies next to the X-rays. The *E* layer is ionized by ultraviolet radiation and, apparently, to a considerable extent by the sun's X-radiation.

It would seem that in the ionization of the *D* layer, in its lower part, a decisive part is played by cosmic radiation, and in the intermediate region, by ultraviolet and X-radiation. Electrons forming in the *D* layer get attached to neutral atoms and molecules at night and are detached in the daytime under the action of the visible radiation of the sun.

To account for the origin of ionization in different layers of the atmosphere we need numerous data obtained by direct satellite and rocket measurements. First of all, we have to know how the energy is distributed in the solar spectrum in its visible and invisible portions and how it is absorbed on its way down through the earth's atmosphere.

We must also know the chemical composition of the atmosphere at various altitudes, the distribution of density and temperature with altitude, the motion of the air at various heights and much more.

Studying the physical, chemical and electrical

characteristics of the upper atmosphere that vary under the action of solar radiation is the task of a new field of geophysics called aeronomy.

Let us now continue our story about some other phenomena in the ionosphere. The ionosphere has a property that stresses its close relationships with the other, neutral, part of the gaseous envelope of our planet. These are ionospheric inhomogeneities. Though they are not visible to the unaided eye, instruments are capable of detecting large, shapeless, cloud-like inhomogeneities in the ionosphere that behave just like ordinary clouds. They are simply condensations and rarefactions of electrons, from hundreds of metres to thousands of kilometres in size. The higher up in the ionosphere the "radio picture", the larger are the inhomogeneities.

When tuned in to some radio station, you sometimes notice that the reception varies and fades in a rather disorderly fashion. This is due to many factors; quite often it is caused by ionospheric inhomogeneities that alter the conditions of reflection of radio waves arriving at the receiver.

Though this phenomenon is "harmful", it gives clues to events in the ionosphere at various altitudes, where the "wind" is blowing and what its speed is. So far there is no other way to find out such things. There are several ways of determining the winds (called ionospheric drifts) in the ionosphere. The most common one is the technique devised by S.Mitra of India. It consists in the following. There is one transmitter and three receiving sets spaced in a triangular formation that record fading of signals reflected from

the ionosphere. Due to movements of inhomogeneities, the times of intensification and attenuation of signals at the receiving posts are displaced in time differently relative to one another, depending on the direction and speed of the drift of the inhomogeneities.

Knowing this displacement and the distance between receivers, one can determine the direction and speed of such inhomogeneities in the ionosphere. The larger the triangle, the bigger the inhomogeneities that can be measured. By employing a variety of wavelengths it is possible to follow inhomogeneity drifts in different layers of the ionosphere.

Observations of this kind were widely employed during the IGY, and although such drifts are at times masked by random movements in the ionosphere, some regularities have come to light. For instance, in the medium latitudes of the northern hemisphere, winds in the ionosphere at altitudes exceeding 200 km blow mainly north-eastwards, while in the lower latitudes the direction is southwest.

Closer to the equator and at lower altitudes the dominant winds blow to the northeast, the directions being more stable in winter than in summer. The wind speeds are rather high too: hundreds of metres per second in the upper levels of the atmosphere.

All this has to do mainly with the northern hemisphere. In the southern hemisphere, and particularly in Antarctica, there have been very few observations. Only the International Quiet Sun Year has made it possible to improve the picture in this part of our planet. Scientists knew that

during the International Quiet Sun Year the ionosphere would not be so turbulent as during the IGY. This should contribute to the success of wind measurements in the ionosphere.

Research workers believe that drifts in the lower part of the ionosphere are ordinary winds, though stronger than those occurring at the surface of the earth. In the upper ionosphere, however, most likely only charged particles chased about by electrical forces generated by the terrestrial magnet take part in drifts; it may be that neutral particles do not participate in these movements.

During the three decades or so that have passed since the discovery of the ionosphere, its investigation has been confined to a region located below the chief maximum of ionization. It is only during the last ten years that we have learned about what happens beyond, and our knowledge is meagre.

Right after the war, ionosphere researchers obtained a new tool of investigation, the rocket. They began a study of the upper charged layers of the atmosphere in the immediate proximity of the rocket vehicle by means of a variety of probes, traps, and other instruments. Properties of the ionosphere were studied by observing the behaviour of radio waves transmitted from the rocket to earth and back again.

Thus, to determine the density and temperature of ions and electrons in the ionosphere near a satellite or rocket, use was made of Langmuir probes (named after the American scientist Irwing Langmuir who invented them).

The first measurements by means of ion traps

installed in a satellite were made in 1958 by Sputnik 3, the third Soviet satellite. To measure the electron density in the ionosphere, wide use was also made of radio-interference devices that had been invented for other purposes by the Soviet scientists L. I. Mandelshtam and N. D. Paleksi way back in 1930 when satellites and rockets were only to be found in science fiction.

The story goes that over a hundred years ago the Austrian physicist Christian Doppler was walking with his son in the outskirts of Vienna when a loud steam locomotive came chugging round the bend and the boy asked why it was that when the train approached the whistle's pitch went higher and higher, and when the train moved off into the distance the tone became lower. Whether or not it was the curiosity of the boy that made Doppler look into this matter we do not know, but the Doppler effect, as it later came to be known, became a virtual storehouse of information for specialists in a wide range of fields.

The Doppler effect consists in the following. When a source of some kind of emission—sound, light or radio-wave, it makes no difference—is moving relative to a stationary observer, the waves arrive at the observer with a frequency that differs from that emitted by the source. If the source is approaching, the frequency is higher, and if it is receding, the frequency falls off.

As has already been mentioned, the speed of propagation of radio waves in the ionosphere is less than that of light, and the longer waves propagate more slowly than short waves. What is more, there is a difference in refraction of waves

of different frequency during their passage through the ionosphere. The result is that radio waves moving through the ionosphere are scattered.

A rocket or satellite is equipped with a transmitter emitting two frequencies, one of which is a whole number of times greater than the other. Their variations in time are brought into agreement. At the receiving station on earth the lower frequency is increased the necessary number of times so as to make the waves comparable in frequency.

The transmitter on the satellite or rocket is in motion relative to the receiving station, and so we observe a change in frequency, the Doppler effect; on approach, the frequency increases, when the transmitter recedes from the observation post, it diminishes. In the ionosphere scattering makes waves of different frequency refract differently, and propagate with different velocities. For this reason, they arrive at the receiving station with beats—periodic intensification and fading in the audibility of the signals, which enables one to determine the electron density of the ionosphere. During the IQSY, Soviet satellites of the Cosmos series and Electron series carried “Mayak” (Beacon) transmitters that permitted measuring the electron density by utilizing the Doppler effect.

The first flight into the upper portion of the gaseous mantle of the earth took place on October 4, 1957, when the world's first artificial satellite, Sputnik 1, was launched as part of the IGY programme. This opened a window into the outer ionosphere which hitherto had been hidden from investigators by a maximum-density shield. The

apogee of the first satellite was 947 km, perigee, 228 km. Thus, most of the 27 days of its radio life, the satellite spent in the outer ionosphere.

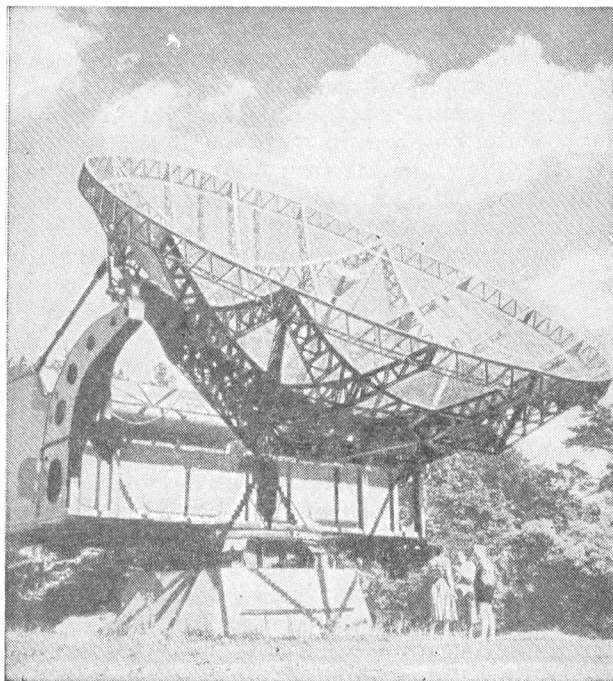
Sputnik 1 had transmitters operating on frequencies of 20 and 40 MHz (megahertz or megacycles per second). Their historic "beep-beep-beep" heralded a new era in the science of the earth and circumterrestrial space.

You probably know that due to the refraction of light rays in the earth's atmosphere, celestial bodies are seen somewhat above their actual place in the sky. That is why at sunrise we see the solar disk as a whole, whereas in the absence of refraction a portion would be hidden from us below the horizon. A satellite also has its "radio-rise" and "radio-set". Radio waves sent from a satellite beyond the ionosphere are refracted in it and arrive at the receiving station when the satellite is no longer (or not yet) there.

All ground-observation stations tracked the signals of the first Soviet satellite. The time of radio rising and radio setting could be judged on the basis of enhanced or attenuated signals. Its position (co-ordinates) was obtained from the ephemerides (tabulated data of the motion of the satellite). Vertical sounding from the earth reported on the state of the ionosphere from its lower fringe to the principal maximum.

Utilizing these findings, scientists determined that the electron density above the principal maximum falls off more slowly than it increases when approaching it from the earth and that the number of electrons above the maximum is roughly three to four times that under it.

The first measurements above the maximum of electron density (up to 473 km) by means of rocket-carried radio-interference instruments were carried out by Soviet workers on February 21, 1958. Later, the method was employed by scientists in other countries. During the IQSY, the record was set by American geophysicists who



Radio telescope (Czechoslovakia)

measured the electron density at 5,500 km above the earth's surface.

Our natural satellite the moon is also used in studies of the ionosphere. The first experiments were conducted in 1957 by the radio observatory at Jodrell Bank in England. Radio waves reflected from the moon told us a lot about the properties of the ionosphere that they traversed on the way out and back. Similar investigations were conducted in the United States in 1959 and 1960. Radio reflections from the moon were obtained on radar frequencies of about 150 and 400 MHz.

These measurements were found to agree with the material obtained in radio observations of the first satellite. The electron concentration in the outer ionosphere proved to be about three times that in the lower ionosphere. During the IQSY lunar radar studies were carried out systematically from moonrise to moonset.

Sounding from above, from a satellite, opened up great opportunities for investigating the upper part of the ionosphere. This was done for the first time on a joint Canadian-American satellite, Alouette, launched into orbit at the end of September 1962. The ionospheric station of the satellite with a frequency varying from 0.5 to 12 MHz was manufactured in Canada, while the launching rocket was made in the United States.

Alouette is in a nearly circular orbit 1,000 km from the earth, the orbit inclined 80° to the equator. Data gathered by this space vehicle are received by 14 ground stations, and have so far supplied great quantities of information about the distribution and behaviour of the electron density above the principal maximum.

It has been confirmed that above the layer of maximum electron density there is a much slower decline in numbers of electrons with height than the increase that occurred below the layer. And at 1,000 km from the earth, the number of electrons per cubic centimetre is roughly the same as in the *D* layer. It was found that the equatorial anomaly detected by ground-based ionosphere stations extends up to an altitude of about 600 km and is probably the result of an expansion of the ionosphere above the equator in the daytime.

It has been noticed that during magnetic storms at geomagnetic latitude about 55° to 60° there is an appreciable fall in ionization and that the ionosphere above both polar caps is always in a diffuse state.

Observations on the Alouette spacecraft showed that the ionosphere strives to align itself with the lines of force of the earth's magnetic field. This explains why not only the very long wavelengths but also the shorter ones (up to 50 metres) can travel in the outer ionosphere between one hemisphere and the other numerous times along the lines of force of the magnetic field.

Now let us return to the question of the chemical composition of the upper layers of the atmosphere. For a long time, information was obtained indirectly, by studying the spectra of auroras and night airglow. Air samples taken by sounding balloons and rockets told us about the composition of the air roughly up to 100 km above the earth.

High-altitude findings began to multiply after it was found possible to carry out chemical air tests directly in the ionosphere by means of in-

struments carried on satellites and rockets. Now chemical robots like magnetic and radio-frequency mass spectrometers do the job. They operate from 100 km upwards. A mass spectrometer can sort out charged particles according to atomic mass units and determine their quantitative ratios. It can also determine the composition of neutral particles at altitudes of about 200 km, and charged particles at about 1,000 km and even higher.

Numerous analyses of the gaseous composition of the atmosphere demonstrate that up to approximately 90-100 km the atmosphere may be considered homogeneous, since, with the exception of such slight components as water vapour and ozone, its composition is practically the same. The explanation is that up to these heights the atmosphere gets thoroughly mixed.

Upwards of roughly 100 km the composition of the atmosphere begins to change perceptibly. Under the impact of the sun's ultraviolet radiation, a dissociation process sets in: first oxygen molecules break up into separate atoms and then, at greater altitudes, nitrogen molecules. As a result, we begin to encounter atomic oxygen and nitrogen in increasing quantities along with molecular oxygen and nitrogen.

As has already been mentioned, there is also a parallel process of ionization of atoms and molecules of the air. Neutral and charged atoms and molecules of the air combine chemically to form new chemical compounds. In the *E* layer of the ionosphere, mass spectrometers noted both positive ions of molecular and atomic oxygen and large quantities of positive ions of nitrogen oxide.

Above 100 km the density of the atmosphere falls off appreciably, and so collisions between particles are fewer, and the free-path lengths of the particles increase. Diffusion and gravitational forces become increasingly important in the distribution of gases in altitude: the lighter gases strive upwards, the heavier ones move downwards.

American measurements in 1963 confirmed the findings obtained by the Soviet Sputnik 3 that at less than 250 km (at the surface as well) the principal role in the composition of the atmosphere is played by molecular nitrogen; above 600 km, the light gas helium is dominant, and in the intermediate region, it is atomic oxygen.

An extensive programme of mass-spectrometric investigations was carried out during the IQSY by the Soviet satellites Electron 1 and Electron 2 and the American space vehicle OGO 1 (Orbiting Geophysical Observatory). The Soviet Electron satellites recorded positive ions between 400 and 3,000 km.

Curiously, no molecular ions of nitrogen, nitrogen oxide or oxygen were detected, although Sputnik 3 registered them. This indicates that at 400 to 500 km the number of molecules of these gases diminished when passing from maximum to minimum solar activity. As usual, it is the sun with its whimsicalities.

Positive ions of hydrogen were registered at all altitudes, and at 500 to 700 km up the number of positive hydrogen ions was equal to the number of positive ions of atomic oxygen. Helium ions at any of these altitudes made up only a small portion of the total ionic population.

Whence researchers concluded that during minimum solar activity there is apparently no separate layer of helium ions. This confirms the fact that the thickness of the region of predominant positive helium ions depends on the temperature. The region is broad at high temperatures (during maximum solar activity) and hardly noticeable at low temperatures (during solar minimum).

The type of orbits of the satellites and the probes aboard the Soviet Cosmos vehicles and the American Explorers showed that besides changes from day to night and through the seasons of the year, the temperature of the upper atmosphere is very sensitive to changes in the activity of the sun. Likewise, it varies with the latitude, increasing from equator to the poles.

Above 200 km, the mean monthly night temperature during maximum solar activity reaches $1,500^{\circ}\text{K}$ (Kelvin), during minimum, only 600°K . In the daytime the temperature of the neutral atmosphere is 30 per cent above that at night. Approximately 300 km from the earth the electron temperature in the daytime is roughly twice that of positive ions. Which means that the atmosphere here is no longer a uniform medium: different particles move almost independently of one another.

Studies of the ionosphere are important both in a purely scientific sense and practically. Supported by these data, scientists tell radiomen what wavelength to use for communication between specific places and what changes to make when radio-wave propagation changes due to events in the ionosphere.

Knowing how the ionosphere depends on the

sun's behaviour, it is possible, by more or less reliably predicting events on the sun, to make up a schedule of radio communications for a whole season and to issue forecasts on disturbances in the ionosphere for several day ahead. Ionospheric data will help in the designing of transmitters and types of antenna for reception and transmission.

A prominent American scientist once calculated that information obtained in ionospheric research has saved the world hundreds of millions of dollars. It is hard to say just how true this is, and of course scientific achievements are not so easily measured in money. But one thing is certain, and that is that the extensive and systematic studies of the properties of the upper atmosphere have already given and will continue to yield enormous dividends to pure and applied science.

Research into the ionosphere serves a great many sides of human activity. Radio communication and broadcasting, radio navigation on land, at sea, in the air and in cosmic space are impossible without a deep knowledge of the behaviour of this temperamental layer of the earth's atmosphere.

The laboratory physicist also needs more information about the laws governing the ionosphere: this is cold plasma in the most common form about us. Aerodynamicists preparing airliners for long-distance high-altitude flights also have to know the properties of this medium through which their aircraft will fly and with which their surfaces will interact.

Geophysicists are now busy processing the ex-

tensive materials and findings of the IQSY obtained by 270 ionospheric stations scattered over all continents. There are 25 Soviet stations among them, including such important ones as the drifting "North Pole" stations, the Antarctic "Vostok" base and many others.

Scientists are focussing attention on the Antarctic because this was the first time that such observations were carried out there during minimum solar activity. No less important are the present observations in the outer ionosphere that are being conducted on an unprecedented scale.

Atmospherics—child of thunderstorms

You are sitting back listening to your favourite radio programme when all of a sudden a terrible crackling noise spoils the whole show. What could it be? There is no industrial noise or other interference close by. The actual source of trouble is not on any adjacent street but in distant Argentina or on the island of Java.

Every day there are some 16,000,000 thunderstorms on this planet. Even if each one lasts only an hour, there will be about a thousand eight hundred storms raging at any one time; every second, lightning flashes at least a hundred times and there are just as many crashing claps of thunder.

Most thunderstorms break out in the equatorial belt, in Africa, South America, Indonesia. There are vast expanses here with over two hundred thunderstormy days a year. And though these violent events take place far away, their effects are felt round the world.

The reason is that thunderstorms are accompanied by lightning discharges between clouds and between clouds and the earth. Every flash of lightning is a discharge of electric current of tremendous intensity and enormous instantaneous power output.

Every lightning stroke is attended by the emission of radio waves of a great variety of lengths from the very short to the extremely long, longer than any broadcast by man-made radio stations. These waves spread out in all directions and create the characteristic clicks we hear in our radio sets. They are called atmospherics (generally, simply static).

The short waves produced by lightning are propagated in exactly the same way as those broadcast by short-wave radio stations: in jumps between the source (lightning) and the ionosphere, and between the ionosphere and the ground. In this process they traverse the lower absorbing layer of the ionosphere a number of times and thus decay very rapidly.

Unlike short waves, the long radio waves generated by lightning flashes are propagated in a spherical waveguide formed by the ionosphere and the earth's surface. Here they travel like in a pipe, expending very little energy en route and decaying very slowly with distance. That is why the interference on long wavelengths is worse and active over much larger distances than on the short wavelengths.

Studies of atmospherics help us to develop noise-proof devices, to determine the intensity that has to be created on a given frequency so that the transmission (its useful signal) can wipe

out the noise and intelligibly get the information to the receiver without obnoxious atmospherics jostling it too much.

The intensity of atmospheric interference at large distances from the sites of thunderstorms depends on the state of the ionosphere, which in turn is determined by solar activity. Reduced ionospheric absorption at night leads to enhanced intensity of atmospheric interference on the short waves. Solar flares are accompanied by increased atmospheric disturbance on the long wavelengths. No wonder then that astronomers studying solar flares utilize instruments for recording atmospheric disturbances on the earth in addition to devices aimed at the sun.

Investigators studying atmospheric disturbances have discovered a hitherto unknown mode of radio-wave propagation. It turns out that part of the electromagnetic energy emitted by lightning seeps through the ionosphere and, following the force lines of the earth's magnetic field from one hemisphere into the other, is disseminated into outer space. Here the energy may be reflected from the ionosphere or from the earth and return via the same route to the original hemisphere. There may be quite a number of these inter-hemisphere trips along the force lines of the earth's magnetic field.

An observer can sometimes note several atmospherics due to one and the same lightning flash: one (the first) moving the shortest distance along the earth's surface, and others that pass through cosmic space with a greater or smaller lag. The first atmospheric is of the nature of a crackle, the following ones are like whistles with diminish-

ing pitch. In contrast to ordinary atmospherics they are called whistling atmospherics.

The fall in pitch in whistling atmospherics is due to the fact that the longer wavelengths, having low frequency, are propagated in an ionized medium at lower velocities than the shorter waves. By studying the frequency spectrum of whistling atmospherics, scientists obtain information about the distribution of ionization in the magnetosphere over very large distances from the earth and about how it varies depending on the sun's activity.

That is why whistling atmospherics were under such careful study during the IQSY.

Besides being generators of radio interference, thunderstorms are quite obviously harmful in many other ways. This unharnessed force of nature carries off thousands of lives a year despite the wide use of lightning rods. Lightning damages dwellings and industrial buildings, high-voltage transmission lines, causing fires, aircraft crashes and endless other trouble. Quite natural therefore that all weather services of the world are keenly studying thunderstorms and lightning.

It is interesting to note that radio and the first instrument for studying lightning were born at the same time. A. S. Popov quite rightly called his first radio receiving set a storm indicator, for it did record lightning discharges. Today, discharges are not simply recorded; cathode radio-direction-finders are used to determine the coordinates of the site of a thunderstorm. Direction finding of atmospherics enables one to trace out the development of storms, their shifting position, the movement of warm and cold air masses, on

the boundaries of which (warm and cold fronts) thunderstorms originate. These investigations occupied an important place in the programme of the International Quiet Sun Year.

Scientists study the geographic distribution of lightning, the diurnal and seasonal variations of frequency of its occurrence, the spectral distribution of energy emitted by lightning, its effect on radio transmission on various frequencies during different times of day and throughout the seasons.

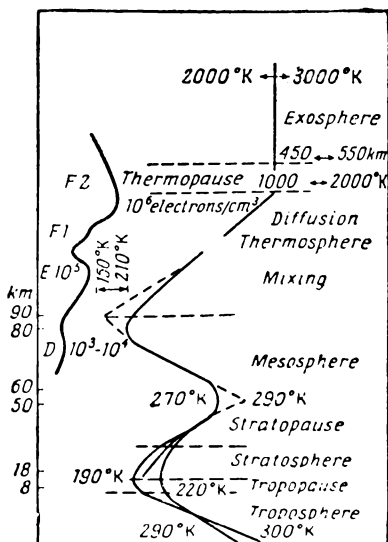
Aside from atmospheric, researchers are interested in other low-frequency emissions: ionospherics, which are believed to be generated in the magnetosphere or in the ionosphere by streams of charged particles arriving from the sun. Much will undoubtedly be learned from all these studies of the ionosphere and magnetosphere and the influence of the sun on them.

Does the sun make the weather!

Does solar activity have any effect on the weather, the climate, and the atmospheric regime? This question has long since engaged meteorologists. But before giving an answer, we must find out what changes in the various layers of the atmosphere are generally caused by solar activity.

The gaseous shell of the earth (the atmosphere) is uniform, but several regions may be singled out that have different properties and that respond differently to solar events.

According to one of the most common models, the atmosphere may be divided into the following spheres: the troposphere that extends on the



Structure of the atmosphere. Regions and temperatures are indicated on the right; position of ionosphere and electron density at maximum on the left

average up to 8 km at the poles and to 16 km at the equator, the stratosphere, which reaches 50 km, the mesosphere up to 80 km, the thermosphere to 300 km, and finally, the outermost, exosphere, upwards of 300 km. Between them lie the intermediate layers, or "pauses": the tropopause, stratopause, etc.

The names of the various spheres come from the Greek, different terms designating the salient features of each region. "Tropo" signifies variable, and the troposphere has the meaning that all basic meteorological changes, including mix-

ing of the atmospheric gases, occur only in this layer. When the stratified layer—the stratosphere—was discovered, it was not known that the temperature there varies with altitude, and it was believed for this reason that there should not be any movements in that region and all gases would arrange themselves in layers: the heavier ones below and the lighter ones above. Today we know that the air in all the three lower spheres is mixed due to atmospheric movements.

Perceptible changes in the composition and distribution of gases with altitude occur in the thermosphere, which gets its name from changes of temperature with altitude. For example, at about 100 km, the amount of atomic oxygen is roughly equal to that of molecular oxygen, while at about 200 km it exceeds molecular oxygen by 15 times. The variation of composition with altitude takes place due to the partial dissociation of oxygen and nitrogen and as a consequence of their diffusional separation.

The name “mesosphere” signifies an intermediate sphere. The outer layer of the gaseous shell of the earth is called the exosphere. It was believed that due to the high temperature, individual particles of air in this region would be able to overcome the forces of gravity and leak out into space. “Exo” in Greek means “outer”, hence the name. Now, however, we know that most of the particles of the exosphere are electrically charged, not neutral, and, hence, are kept in by the magnetic field of the earth.

There is no equality between these regions. Although the troposphere is the thinnest, it contains the bulk of the air mass of our planet—

about 79 per cent. The stratosphere contains another 20 per cent, and only about 1 per cent of the entire atmospheric mass is found in the vast expanses of the remaining layers. This distribution of air masses has to be taken into account when investigators study the interrelations of the layers of the earth's gaseous envelope.

The above model is of course very approximate, and it may very well be that further research will alter it somewhat. But today it fits the level of our knowledge and is convenient for an analysis of observational data that are accumulating at an increasingly rapid rate due to the technological break-throughs of recent years which have yielded sensitive instruments and apparatus for studying the upper atmosphere via rockets and satellites.

Incidentally, very important facts for meteorology and the physics of the atmosphere may be obtained indirectly without sending scientific instruments aloft in spacecraft. The density and temperature of the atmosphere at high altitudes may be obtained just by watching satellites, recording their velocities and noting how they are decelerated by atmospheric friction.

Still, scientific workers were in for a surprise. Just before the commencement of the IQSY, in 1963, observations of satellites indicated that the density of the atmosphere at 650 km altitude had diminished almost 50-fold compared with 1959. This was due to the fact that at the height of the IGY, when the sun was unusually stormy, the thermosphere heated up, expanded, and its mass got redistributed in such a manner that at considerable heights satellites encountered a good

deal of resistance. And by the onset of the IQSY, when the sun had calmed down a bit, the thermosphere cooled off and contracted, and satellites moved more freely at the same altitudes. Particularly sensitive to variations in atmospheric density were the light, balloon-type satellites of relatively large diameter.

Observations of the rate of deceleration of a satellite and other experiments have shown that at about 300 km the temperature changes from day to night by a factor of two: in the daytime it is about $1,800^{\circ}\text{K}$ and at night it falls to 900°K . A comparison of the rate of decay of satellite velocity with the intensity of streams of radio emission coming from the sun on wavelengths of 20 and 10 cm revealed a remarkable relationship between these phenomena: the higher the radio emission, the lower the speed of the satellite. This would seem to indicate that the "radio stations" of the sun act as a brake on space vehicle movements. But this is not exactly so. The radio emission itself is not responsible for changes in the upper atmosphere. The relationship here is of a secondary nature.

The sun's radio emission in the decimetric range is, as we have already had occasion to say, a good indicator of solar activity. It is excited in solar flares and is radiated by the corona of the sun in sunspot regions. Above sunspots, the corona is condensed and besides radio waves it emits soft X-rays and hard ultraviolet radiations, which are absorbed in the thermosphere causing it to heat up and expand.

Researchers made a detailed analysis of the movements of the American balloon satellite Ex-

plorer 9 and found retardation repeatedly correlated with magnetic storms. Particularly pronounced were the effects produced during one of the greatest magnetic storms in the past decade that raged round the earth on November 13, 1960. The drastic change in the speed of the satellite at that time may be explained only if we assume that the temperature in the thermosphere increased by 500° - 600° during the storm.

Thus, we see that the relationship between solar activity and variations in temperature and density of the upper layers of the atmosphere was established definitely after only a few years of observations. In just another few years we shall be able, on the basis of solar activity, to give confident forecasts of the "weather" in the upper atmosphere at the fringes of our ocean of air.

Now how is solar activity correlated with meteorological phenomena in the troposphere, at the bottom of the ocean of air where we live?

We all know that weather processes in the troposphere (which include circulation of the atmosphere) and the water cycle on the earth are ultimately governed by the influx of solar energy. This is an established fact of long standing and familiar to every schoolchild.

The question here is different: Do meteorological phenomena—the weather and the climate—reflect the cyclic and irregular variations in solar activity that resemble (even remotely) the relations with the sun that exist between the upper layers of the atmosphere and other geophysical phenomena, such as the magnetic field, the ionosphere, and the auroras?

William Herschel, the great English astrono-

mer of the end of the eighteenth century and the beginning of the nineteenth, a man of versatile talents and the builder of the largest telescopes in the world at that time that helped him to discover the planet Uranium and to detect the existence of a thermal infrared part in the solar spectrum, was apparently one of the first to relate solar activity to changes in the weather and even to high and low wheat harvests.

Since then, for nearly 100 years, studies of the relations between solar activity and meteorological events have never ceased. There is a tremendous literature devoted to the problem. During this time, sunspots and other manifestations of solar activity have been correlated with the whole range of weather phenomena: rain, hail, snow, cloud cover, thunderstorms, cyclones, anticyclones, the intrusion of polar air masses and what not. Correlations with the sun have been carried out by separate weather stations and by large groups of observatories and stations and have embraced vast areas of the earth. Data for separate days, and mean values for whole seasons and even decades at a time have been utilized.

And the results? Even the biggest enthusiasts prone to see the hand of the sun in every event here on earth cannot but admit that the results of these correlations cannot serve as a basis for accurate short-term or long-term weather forecasting. Even if the relationship in some region proved to be a nice fit (the weather and solar activity being in agreement), in another region nothing of the kind was observed.

When those firmly convinced of the existence of such a relationship turned from emotional talk

to precise scientific characteristics, it was found that the coefficient of correlation (the degree of coincidence expressed numerically) was always slight. It was never possible to reliably connect changes of the weather in some region of the earth with the cycles of solar activity.

That is why a special international commission on the study of solar and terrestrial phenomena, summing up, in 1963, the results of an extended investigation of meteorological phenomena in the troposphere, came to the conclusion that at least in the near future a definitive solution of the problem is not to be expected.

The reader will naturally want to know why some layers of the atmosphere react to changes in solar radiation while others do not. As you have seen, all phenomena that exhibit a relationship with solar activity are in one way or another caused by the absorption of corpuscular, X-ray and ultraviolet radiation of the sun in the upper layers of the earth's atmosphere. This radiation is weakened as it penetrates deeper into the atmosphere. The last intense absorption of ultraviolet radiation in the stratosphere is what leads to the formation of the layer of atmospheric ozone.

Radiation absorbed in the upper atmosphere of the earth originates mainly in the upper layers of the sun's atmosphere: in the chromosphere and the corona. And these are precisely the portions of the gaseous shell of the sun that experience the greatest changes with the cycle of solar activity.

Now meteorological processes in the troposphere are associated with the arrival on the earth of infrared, visible and, partially, ultraviolet radiation of long wavelengths. This "meteo-

logical" portion of the radiation comes to us from the photosphere of the sun, which does not experience such large variations with the solar cycle as the higher-lying layers of the sun's atmosphere.

We know that sunspots even during the years of maximum development of solar activity do not cover, on the average, more than one two-thousandth of the surface of the photosphere. What is more, their temperature is only $1,500^{\circ}$ - $2,000^{\circ}$ C lower than that of the photosphere. Besides, the apparently slight fall in radiation from the sunspot region is fully balanced by intense emission from regions of faculae.

To find the quantity of energy coming from the sun to the earth, scientists began to calculate the "solar constant", which is the quantity of heat per minute falling on a one-centimetre square perpendicular to the sun's rays at the boundary of the atmosphere. So far, measurements have been conducted only on the earth, and the quantities that are expected at the boundary of the atmosphere are calculated by introducing corrections for absorption and scattering of radiation in the earth's atmosphere.

Of course, these corrections cannot be particularly accurate since the state of the atmosphere is constantly changing. Yet, the solar constant is indeed very constant, its mean value coming out to about two calories with deviations in individual measurements not exceeding 1-2 per cent.

Two calories per square centimetre per minute? Surely that is not much in this age of truly astronomical figures. But it amounts to many tens of thousands of millions of kilocalories for the whole

surface area of the atmosphere in one year. All the power stations of the world combined do not even remotely approach this figure.

Not all this energy arrives at the earth in the form of direct sunlight (direct radiation). A considerable portion is dispersed by the atmosphere and clouds and arrives at the surface in the form of scattered radiation. Some of the energy is absorbed by the individual components of the atmosphere—ozone, water vapour, carbon dioxide—and only later is re-radiated earthwards and into outer space.

The absorption and scattering of radiation differs in different portions of the spectrum and for different zenith angles of the sun. Part of the energy of sunlight falling on the earth is reflected, while the other part is absorbed by the earth's surface and heats it up. The absorption and reflection of solar radiation are determined by the properties of the locality where the rays impinge or, as specialists put it, by the properties of the underlying surface. In turn, the heated earth becomes a source of thermal radiation.

Radiation emitted by the earth is absorbed in the atmosphere mainly by water vapour and is emitted partly upwards and partly back to the earth. The air near the surface of the earth heats up both because of radiation from the surface and due to convection: warmer air rising upwards and cool air coming in to take its place.

Because of reflection from the earth and the atmosphere, mainly from clouds, a substantial portion of the radiation coming from the sun (about 35 per cent) is not utilized in the thermal budget of our planet and goes off into outer space.

One of the problems during the IQSY was to register all the adventures solar radiation experiences in the earth's atmosphere. A large network of ground-based actinometric stations measured the direct and scattered radiation arriving at the earth and the radiation reflected from the earth. Special radiosondes measured the incoming and outgoing radiation at various altitudes. The same measurements are made at still higher altitudes by weather satellites.

The meteorological programme of the IQSY was broad and diversified. It included observations of the temperature, atmospheric pressure and wind speeds at high altitudes with the aid of radiosondes and weather rockets, and observations of solar radiation about which we have just been speaking. Also important were studies of atmospheric ozone, atmospheric electricity, observations of noctilucent clouds and many other phenomena.

The main difference between the meteorological programme of the IQSY and that of the IGY was that the former was aimed principally at a study of processes occurring in the higher layers of the atmosphere.

To find out what is going on in the upper levels, sounding balloons are sent aloft carrying instruments that report by radio about air density, atmospheric pressure, the temperature, and humidity at altitudes up to 30-32 km, which is the middle of the stratosphere. Wind speeds are found from observations of sounding balloons radiotheodolites. Rockets were more widely used in aerological studies than during the IGY.

In southern Australia, the British Skylark rocket was launched from the Woomera Range; from Wallops Island near the coast of Virginia, U.S.A., the American Nike-Cajun rocket was sent up; at Fort Churchill (the Canadian Arctic) the Black Brant was launched; and at the Krongard Range in North Scandinavia, the Swedish K-63 took off; from the island of Kiushu in the Pacific Ocean the Japanese Lambda 34 was fired into the upper atmosphere, and at Port-aux-Françaises a French rocket Emma took off.

Soviet meteorological rockets streaked through the dull polar night over Kheys Island (Franz Josef Land). At tens, if not hundreds, of places rockets were launched simultaneously to pick up synoptic information about meteorological phenomena at altitudes from 60 to 80 km. Soviet and American workers also performed meteorological rocket sounding from special research vessels equipped with rocket launchers. The Soviet research vessels *A. I. Uoyeikov* and *Yu. M. Shokalsky* are outfitted with such equipment. Several thousand meteorological rockets were launched during the IQSY by various countries.

Systematically and exactly at 00 hours Greenwich Time hundreds of aerological stations staffed with scientists of 70 nationalities released radiosondes to high altitudes. This was done at least once a day, and even more often where possible. All the Soviet aerological stations participating in the IQSY—and there were over 60—sent up sondes twice a day and on occasions of particular scientific interest, four times a day.

Try to picture the launchings every day for two years in stifling equatorial heat, in the Arctic

cold, in tropical rainstorms and Antarctic hurricanes, men trying to handle the unruly balloons which are either pulling upwards or trying to throw the instruments to the ground, or don't want to go aloft, or burst in 70-degree frosts. But it was only in such titanic efforts that the IQSY workers were able to build up a personal file of the atmosphere of our planet.

There is one phenomenon that meteorologists are particularly intent on observing, and that is sudden warming up in the stratosphere. Just a few years ago it was noticed that at times, in winter, when there are cold air masses over the polar regions there is a sudden warming up in the stratosphere at altitudes exceeding 50 km that gradually spreads down to lower levels. At times, the temperature suddenly rises from -85°C to 0°C in just a short time. This warming up sometimes lasts several days and the region it embraces can move from place to place.

Nature put on a display of force like this in the first months of the IQSY. On March 3, 1964, meteorologists in northern Canada were amazed to find that it had suddenly become warm over Baffin Bay. The "bagful" of warm air slowly rolled along towards the pole, reached the northern part of Greenland, hung around there until March 18 and then gradually cooled off over the expanses of the Arctic Ocean. At just about the same time, on the same days, there was a warming up in the stratosphere over Europe, but it persisted only three days.

Such drastic changes of temperature wreak havoc: the circulation of the atmosphere (the movements of air masses) changes character in

midwinter and begins to behave summer-fashion. And the time when winter circulation finally gives way to summer (the time of actual change of meteorological seasons) depends on the number and intensity of sudden winter warmings-up in the stratosphere.

A meteorologist who learns about this from a launched rocket or radiosonde immediately sends a telegram to the appropriate regional centre with the word "stratwarm" and the name of the place where it occurred. IQSY workers will then know that the stratosphere has become warmer, and they will immediately begin preparing for extra radiosonde launchings.

Radiosondes do not usually get beyond the 35th kilometre due to the inner pressure and the cold that burst even the best balloons. Instrument-carrying rockets are used to reach 60-80-km heights, where they record temperature, pressure, wind speeds and directions. This gives a cross-section of the whole warmed-up region in the stratosphere.

Still greater heights are reached by geophysical rockets that bring back diversified information about the composition of the air, its electrical properties, atmospheric emissions, meteors, cosmic radiation, X-rays, atmospheric ozone, and much else of interest to meteorologists, aeronomists, and geophysicists.

The rocket method of sounding the atmosphere might be extended if it didn't have a number of drawbacks: it is expensive and dangerous in densely populated areas: rockets do not always fall where they are intended to. Artillery has been tried in the United States and Canada and exper-

iments in sounding the atmosphere to 100-kilometre altitudes have been successful. Smooth-bore guns were used and they fired special meteosondes of the "Martlet" type. This is cheaper and safer, since shell dispersion is quite small. Weapons of war can be put to creative work after all.

But both rockets and shells have yet another big defect: they yield information only about a narrow corridor of air that extends directly upwards from the experimenters. Quite obviously only limited numbers of shells and rockets can be sent aloft to sound the gaseous envelope of the earth. And they have short lifetimes besides.

But they have a powerful ally, the artificial earth satellite. The great advantage of meteorological observations via satellites is that they permit obtaining information about the state of the atmosphere over the whole planet at practically one and the same time. Besides, satellites permit of constant observation of events over vast areas. They can relate a great deal about processes involving the earth as a whole and occurring in the lower levels of the atmosphere where the weather is formed.

Realizing how promising this work is, the Americans launched a series of special weather satellites—Tiros. The name stands for "Television Infrared Observation Satellite" which gives a good description of the design.

The Tiros vehicles turned out to be extremely useful. During a single year, the Tiros 7 spacecraft sent back about 80,000 photographs showing the distribution of the cloud cover, the movement of storms, snow-covered areas, and the ice situa-

tion on the globe. Eight Tiros satellites including the one that was launched on the eve of the IQSY, December 21, 1963, put into the hands of researchers a total of several hundred thousand television pictures containing useful information. During hurricane seasons they keep under surveillance all the large storms in both hemispheres. Then storm warnings are broadcast by the Weather Bureau for pilots and navigators at sea.

An improved satellite was Tiros 9, which was launched in the middle of the IQSY and has a polar orbit. It reported on weather conditions in the high latitudes where there were few ground-based weather stations. The great advantage of satellites is that they can "keep an eye" on areas that meteorologists find it hard to cover, particularly since the world's ocean area amounts to 71 per cent of the surface of the earth and there is only a handful of weather vessels.

Or take the Antarctic where a surface area exceeding that of Europe is serviced by only a score of weather stations. Then there are the mountainous areas and the deserts. A satellite with television cameras in a 1,000-km orbit can collect information about the cloud cover and ice cover and transmit it to the earth. Special instruments measure the infrared radiation of the earth and the solar radiation. These findings will help to unravel the secret of how solar energy is transformed into the energy of motion of the atmosphere.

Trial measurements of radiation were made on Tiros 2, 3 and 4. These results are now being used to work out a method for determining tem-

perature distribution over the earth's surface and vertically on the basis of satellite data. New satellites will probably be used for observing the distribution of ozone and thunderstorms and also for determining the upper boundary of the cloud cover.

Satellite weather data are thus a big help in perfecting weather forecasts. For instance, satellite photographs of the cloud cover enable one to identify large zones of ascending and descending air masses and yield data on the synoptic situation in extensive regions of the earth. All such data are then fed to electronic computers which perform tens of thousands of mathematical operations a second. Some time ago all this work was done by large teams of experienced calculators who spent weeks on end at a single problem. By that time the weather "forecast" read like a historical document.

Prior to the commencement of the International Quiet Sun Year, scientists of the U.S.S.R. and the U.S. agreed to work jointly on peaceful utilization of outer space and on the launching of American and Soviet weather satellites during the IQSY for the needs of meteorology and weather forecasting. It was decided to set up three special centres in Moscow, Washington, and Australia that would collect and process all the information coming in from weather satellites.

Phototelegraph would be used to send out from these three World Centres prepared weather maps with detailed meteorological data. That is how the IGY and IQSY were linked up. The programme of the International Geophysical Year was highlighted by the launching of the world's

first artificial earth satellite, Sputnik 1; the Quiet Sun Year inaugurated a whole international satellite service. On January 1, 1964, about a thousand meteorological stations round the world raised the flag of the IQSY. Investigations were carried on by a wide range of workers, from the veteran scientists who had made their contribution to the Second International Polar Year of 1932-1933 to young Moscow schoolchildren who were supervised by specialists from the All-Union Astronomy-Geodesic Society in a patrol of noctilucent clouds in strict accord with the IQSY programme.

It is interesting to note that the young Moscow geophysicists were joined by their colleagues on the other side of the ocean. Two thousand students in Virginia and Maryland and the District of Columbia (U.S.A.) took upon themselves daily observations of clouds, wind, humidity, and temperature during the passage of a weather satellite overhead. The point is that satellites are not yet able to give clear-cut photographs of clouds less than 2 km in diameter. The schoolchildren—students of the fifth and sixth grades of two hundred schools—working the Sky Watch, contributed many useful observations, and the materials, like those of the Soviet schoolchildren, were sent along with the findings of research scientists to the World Data Centres.

The British weather service designed instruments for measuring the distribution of ozone in the atmosphere and installed them in a satellite, Ariel 2, that was launched on March 27, 1964, from the United States' launching site on Wallops Island.

Ozone studies became rather widespread during the IQSY. And rightly so, because ozone is a special form of oxygen, the molecule containing three atoms instead of the normal two. The life of O_3 molecules is closely bound up with the action of the sun on the gaseous envelope of our planet. Ozone is found everywhere in the air but in very small quantities, and so the total amount is almost negligible: if it were under ordinary atmospheric pressure the whole ozone layer above the earth would be less than 0.5 cm thick.

There is not much of it, but the role it plays is great: ozone possesses a marvellous capacity to actively absorb excess ultraviolet radiation coming from the sun, which would otherwise be lethal to all living beings on the earth. Ozone is found in all three lower levels of the earth's atmosphere, but most of it lies in the stratosphere, where its lifetime is longest. Maximum ozone density lies at about 20 km.

How is ozone produced? A portion of the oxygen molecules absorb ultraviolet radiation and dissociate into separate atoms, which combine with whole oxygen molecules to form the strange O_3 . This molecule is unstable and under the action of the ultraviolet rays that gave it birth soon perishes decaying into the original parts: the more viable O_2 molecule and a free atom of oxygen. This process is constantly going on, but ordinarily no dynamic equilibrium sets in, and there is either a greater or smaller concentration of ozone in the air.

The amount of ozone in the atmosphere differs at various times of the year. It also varies with the time of day or night and with geographic

latitude: there is more ozone in the polar regions and during spring. But no definite relationship has been established with the solar cycle. True, at times the total quantity of O_3 in the atmosphere can change drastically in just a few hours, but scientists do not know why this happens.

Temperature rises in the stratosphere are due to absorption of the short-wave ultraviolet rays by ozone, which also absorbs a substantial portion of the long-wave earth radiation. Radiation absorbed by ozone is re-radiated and some gets back to the earth. Thus, ozone, like water vapour at the earth's surface, plays an important role in preserving heat in the troposphere. No wonder then that ozone was studied with particular care during the IQSY.

During the IQSY, meteorological stations in all countries launched ozone-sounding balloons which yielded information about any changes in the abundance of this gas in the air during the occasional flares of the quiet sun. Ozone was also studied by aircraft, thus enabling a vertical and horizontal analysis of ozone concentration.

In addition, there was a special airborne ozonometric laboratory of the Chief Geophysical Observatory named after A. I. Voeikov (Leningrad). Scientists flew hundreds of hours over the northern and central regions of the country investigating processes involving this capricious gas.

Nortilucient clouds are luminous silverish-white formations with an occasional bluish hue reminiscent of clouds residing in the upper levels, such as cirrus and cirrostratus clouds. But unlike the latter, they are not seen in the upper troposphere but in the mesosphere at about 80-km

altitude where we find the second and deepest temperature drop. Noctilucent clouds are so transparent that the light of the stars and moon passes through them losing hardly any strength.

Noctilucent clouds often have a fine pattern with a pronounced wave-like structure. They are seen in the summertime during twilight in latitudes between 45° and 70° only when the sun lies 6° to 16° below the horizon. If the sun is just below the horizon, the sky is so bright that the luminous clouds are swamped. Below 16° the atmospheric levels inhabited by these clouds are in the dark.

Extended observations in Ashkhabad (latitude 37.5°) indicate that in latitudes less than 45° noctilucent clouds are not observed; they may put in an appearance above the 70th parallel but are practically invisible because the sun does not go below the horizon more than 6° in the summertime.

The filamentary structure of noctilucent clouds bespeaks high wind speeds that blow in their domain. Measurements indicate that these wind-blown luminous structures cover 40 metres a second on the average, sometimes even 200 m/s.

This beautiful phenomenon of nature first attracted attention in 1883 following the violent volcanic eruption of Krakatau in the Sunda Strait between the islands of Java and Sumatra. The stupendous quantities of volcanic dust thrown to heights of about 80 km scattered in the atmosphere giving rise to magnificently brilliant sunsets over the whole world for a number of years.

No wonder then that numerous observations

were made of noctilucent clouds during this period. Interest in them later fell off, however, until the IGY. True, even then only in the Soviet Union were observations put on a broad basis where about 200 meteorological stations were on the job. Later, other countries also began mass-scale observations of these luminous clouds.

This phenomenon has now been filmed and photographed in theodolite observations in the Institute of Applied Geophysics of the Chief Management of the Hydrometeorological Service in Moscow and by their colleagues of the Geophysical Institute in Alaska together with scientists of England and Sweden. Also involved in the observations were some hundred stations in North America, Greenland, and Iceland, dozens of stations in England and Sweden, and over two hundred stations in the U.S.S.R. Noctilucent clouds have likewise been hunted by air crews of the Pan-American and Alaskan air companies.

Prior to the IQSY, there were very few reliable observations of noctilucent clouds in the southern hemisphere, and the first photograph was made only in January 1965. Today 50 stations conduct observations of noctilucent clouds in this sparsely inhabited hemisphere.

The fact that luminous clouds were first observed after the eruption of Krakatau suggested that they were produced by minute particles of dust, the products of volcanic eruptions. Observational statistics however do not support this view.

Then what are noctilucent clouds made up of? For a long time this was a mystery. Even during

the IGY the question was debated whether it is cosmic dust, minute particles from the earth's interior thrown into the heavens during volcanic eruptions or the remnants of burnt-up meteors.

In 1962 Swedish scientists using two rockets (one of which was launched when noctilucent clouds were observed and the other when they were not) sampled and analyzed particles from the mesopause. It turned out that in noctilucent clouds the number of particles was from one hundred to a thousand times greater than in their absence and that the particles picked up in the clouds were much larger because they were enveloped in a shell of ice.

This would seem to be corroborated also by the fact that an artificial luminous cloud in the mesopause is produced by the combustion products of the solid fuel of rockets, the fuel being rich in water vapour and hard particles. However, the nature of the noctilucent clouds has not yet been deciphered completely and it is hard to say what significance their secret has for an understanding of the general dynamics and thermodynamics of the atmosphere and weather forecasting.

The International Quiet Sun Year has hastened the time when the relations of our sun with the air mantle of the earth will become clearer and when fully reliable forecasting of the weather will become a routine matter. Lomonosov was clear on this point when he said: "People would have nothing more to ask to God if they could predict the weather."

Galileo: "Provando e Riprovando"

There can be no doubt whatsoever about the effects of solar activity on many geophysical phenomena, in particular on events in the upper levels of the atmosphere and in the outer space around the earth. This is evident in variations of the magnetic field of the earth, in variations of cosmic radiation, and in the frequency and intensity of auroras, in variations of temperature and density of the upper layers of the gaseous envelope and its ionization, and disruptions of radio communication. These effects are evident not only in a statistical analysis but also in direct correlations of individual phenomena occurring on the sun and on the earth.

Can it be accidental, for instance, that intense solar flares are invariably followed by specific events on earth? We have already mentioned the fact that a few minutes after the onset of a flare, observatories note enhanced radio interference. Together with the radio emissions associated with the flare, the earth is bombarded by ultraviolet radiation and X-rays from the flare. It is attended by a sudden increase in the absorption of short radio waves.

Enhanced ionization in the lower level of the ionosphere leads to a build-up of electric currents there which are responsible for the diurnal variations of the magnetic field. This gives rise to a special type of geomagnetic disturbance.

Very often, just a few tens of minutes after the commencement of a solar flare, we may find an intense absorption of radio waves in the polar

caps (the Arctic and Antarctic). This absorption is not caused by ultraviolet radiation and X-rays of the sun but by streams of protons expelled from the sun during the flare.

Magnetic storms and ionospheric disturbances set in a day and a half to two days following a flare. They are usually attended by intense auroral displays that sometimes reach almost to the equator. Violent magnetic storms are also accompanied by a decline in cosmic-ray intensity. Rapid changes in the magnetic field during magnetic storms build up electric currents induced in the conducting layers of the earth.

Great changes take place in the ionosphere during magnetic storms: the height of the ionosphere goes up and the density of ionization goes down. During storms, the temperature and density of the upper atmosphere increase, thus even affecting the motion of satellites. Such storms also bring about drastic changes in the radiation belts of the earth.

There is not the slightest doubt that the trouble maker is the sun every time. This relationship between solar and terrestrial phenomena has been established with complete reliability, and the task of the International Geophysical Year and the International Quiet Sun Year was to *deepen* our knowledge in this field, to single out fresh peculiarities in these relations and determine their nature and mechanism.

However, regarding certain phenomena the action of the sun is not quite clear, in fact it may even be absent. We have already mentioned the case with meteorological phenomena in the stratosphere, where, despite numerous correlations in-

volving a variety of indices of solar activity, no reliable connection has yet been established.

In the hundred years of sun-earth studies, one can find quite a number of instances of things ascribed to the sun of which it was innocent. At one time it was quite the vogue to relate solar activity with the outbreak of wars and revolutions, the rise of great men, the fall of empires and other social phenomena. Today these things are not taken seriously by anyone.

On the other hand, it is commonly asserted that tree rings are in some way connected with solar activity. On this basis, attempts have been made to picture the pattern of solar activity in past ages long before there were any observations of the sun's activities; the enormous coniferous sequoia trees of California that live up to two thousand years and the thousand-year juniper tree of Central Asia were studied. Earthquakes have also been correlated. Attempts are still made to find some kind of relation between them and the level of solar activity.

Papers continue to be written about supposedly established relations between solar activity and biological phenomena.

Some authors maintain that periods of mass multiplication of locusts, beet pests, rodents and other pests are somehow connected with cycles of the sun's activity. Some correlate them with maxima, others with minima of solar activity.

In the 1930s, a serious German medical journal carried an article in which statistics of sudden deaths due to accidents and suicides in Berlin were shown to be related to magnetic dis-

turbances. Other researchers maintain that human blood reacts to solar flares. The Italian chemist Giorgio Piccardi claims that the rate of precipitation of minute suspended particles from colloidal solutions is also connected with events on the sun. On his suggestion, experiments were conducted in many places during the IGY for purposes of verification. The experiments are still in progress.

We will not concern ourselves with how realistic the existence of such relations is, not only because they lie outside the scope of the earth sciences and were not included in the programmes of the IGY and IQSY, but also because scientists are still rather divided as to their trustworthiness. There are enthusiasts that are perfectly sure of such relations, but there are also scientists who are extremely doubtful.

The phenomena that we have just spoken about depend on a great many factors, and it is not at all simple to single out the leading one. This requires long-term experimentation and observations under a variety of conditions and the application of specialized techniques of statistical analysis of the observational materials. The simple similarity of two curves that indicate more or less coincident variations of certain phenomena taken over a restricted period of time is not enough to assert the existence of a causal relation.

It is obvious to anyone who is not completely carried away with his pet idea that an event on the sun coinciding in time with a volcanic eruption does not indicate any kind of case-effect relationship. An epidemic of plague occurring

during a solar flare does not in the least signify that the two are related. The ancient Romans recognized the fallacy of arguing from mere temporal sequence to cause and effect relationships (post hoc, ergo propter hoc—after this, therefore on account of it).

The pupils and followers of Galileo, the father of the experimental method of investigation, set up in France an Academy of Naturalists with the motto "Provando e Riprovando", which in the language of today would be something like "check and double check". And this should be the guiding motto of anyone attempting to establish a relationship between the activities of the sun and events here on the earth.

The findings of the IQSY are open to the whole world

The invaluable information about all aspects of sun-earth relations during the period of the peaceful state of the sun has been accumulated through the efforts of thousands of scientists in tens of countries round the world. Numberless figures and masses of numbers and tables, maps and graphs, kilometres of photographic and cinema film have recorded the pulse of the sun and the earth.

To extract from this ore the valuable metal of scientific fact, we have to correlate and analyze all the materials covering every latitude and altitude. Only when the scientist compares the result of solar action on a geophysical phenomenon

on a world-wide scale—from pole to pole—can he construct a substantiated theory.

That is not all, he must have access to material on other geophysical processes to clinch his argument. Finally, the very idea of the IQSY called for comparing events during the period of solar quiescence with the period of the IGY when the sun was turbulent. It was decided therefore to make use of the unique institutions established during the IGY, the World Data Centres (WDC), in the matter of collecting and disseminating observational materials of the IQSY.

The largest such repositories—World Data Centres *A* and *B*—are located in the United States and the U.S.S.R. They contain the results of observations over all divisions of the IQSY programme: solar activity, geomagnetism, auro-
ras, ionosphere, cosmic rays, and meteorology.

Some countries which are not able to set up universal repositories organized World Data Centres *C*, which are centres for the collection of data in some specific discipline of particular interest to the scientists of the given country. For example, Edinburgh, like Moscow and New York, amasses materials of auroral observations, Tokyo concentrates on cosmic rays, London on the ionosphere, etc.

The scientist himself or his institution decides to which centre to send his material. And to be sure a full set of data is available, the World Data Centres operate an obligatory exchange of all materials in their possession. This obviates the danger of loss of unique materials obtained by an observer. It also enables scientists in all countries to utilize such findings. Any special-

ist, no matter where he lives, has the right to obtain any materials that interest him from any one of the World Data Centres. There is no profit made in such transactions: the only thing paid is the cost of duplication and postage.

The World Data Centres built up the fullest possible personal file on the earth and the sun with every fact of their biography recorder between July 1, 1957—the start of the IGY—and 24 hours 00 minutes, December 31, 1965, when the International Quiet Sun Year came to an end.

In addition to the centres of collection and dissemination of data, which are actually huge archives or libraries, a number of world analysis centres have been established to correlate the observational material in the different disciplines and prepare them for publication. Some of these centres, for example on solar radiation and atmospheric electricity, have been set up in the U.S.S.R.

Observations in accordance with the programme of the IQSY came to a close at mid-night January 1, 1966. Primary processing of the materials, their collection in the centres and subsequent exchange between the centres will probably take a number of years. There was also a slight delay in collecting the materials from the distant Antarctic stations: they arrived only at the end of 1966.

However, without waiting for all the material to come into the World Data Centres, thousands of scientists were already poring over hundreds of thousands of sheets and tables, endless tapes of magnetograms and ionograms, and hundreds

of kilometres of film of the sun and auroras. Scores of universities and laboratories, research institutes and computing offices have begun processing material, "washing the sands for nuggets of knowledge". Books and articles are coming off the presses in different languages with many great secrets of the planet earth deciphered.

The IQSY Committee is preparing some ten to fifteen volumes of the "Annals of the International Quiet Sun Year", in which scientists from many countries will bring together the observational results of the various divisions of the IQSY programme. Apart from books and articles, personal contacts of the scientists of the different countries help to exchange information and advance science. In 1966, in Belgrade, an international symposium on solar-terrestrial relations was organized, and the following year the last international assembly of IQSY was convened in London to summarize the scientific attainments of these glorious two years.

The co-operation of specialists working on the sun-earth problem has not ceased with the end of the International Quiet Sun Year. At the Madrid Assembly of the IQSY, that took place in April 1965, scientists suggested continuing joint observations in the future. The International Committee on Space Research plans an extensive programme of investigations in space and on the earth during the period of the coming new maximum of solar activity in 1968 and 1969.

We have entered the age of the research and conquest of outer space and it insistently demands the establishment of a permanent world-wide service of solar observation and the effect of the

sun on the earth and interplanetary space. Nature still has a limitless range of riddles for the inquisitive human mind.

The International Quiet Sun Year will go down in history not only as brilliant scientific achievements, but also as an outstanding instance of peaceful co-operation of scientists in all countries united in the noble work of learning about this world of ours.

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